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FINAL REPORT

FEASIBILITY OF AN ADVANCED THRUST TERMINATION ASSEMBLY FOR A SOLID PROPELLANT ROCKET MOTOR

JPL CONTRACT 953692

A DIVISION OF THIOKOL CORPORATION

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ELKTON, MARYLAND

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T. M. Davis
General Manager

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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1.0 SUMMARY

This program was conceived as the first phase of a multi-phase effort to establish the technology necessary for design of large (~ 1400 to 2000 lbs) solid propellant motors using an advanced thrust termination concept to achieve two-pulse, stop-start operation.

Prior to this program, Thiokol demonstrated that solid propellant burning can be extinguished by delivering fine particles of hydrated aluminum sulfate to the burning surface at high velocity.[1*] This "salt quench" approach to thrust termination assembly design formed the basis for all program work.

Preliminary designs of Thiokol's STAR 37D motor, modified for two-phase operation by salt quench, were prepared at the outset. Experimental effort was then accomplished in the following major areas:

Laboratory Research
Insulation Evaluation Tests
Quench Assembly Performance Tests
Final Demonstration Motor Design and Test

A total of 68 quench tests were conducted in a vented bomb assembly (VBA). Designed to simulate full-scale motor operating conditions, this laboratory apparatus uses a 2-inch-diameter, end-burning propellant charge and an insulated disc of consolidated hydrated aluminum sulfate along with the explosive charge necessary to disperse the salt and inject it onto the burning surface. The VBA was constructed to permit variation of motor design parameters of interest; i.e., weight of salt per unit burning surface area, weight of explosive per unit weight of salt, distance from salt surface to burning surface, incidence angle of salt injection, chamber pressure, and burn time. Compared with the successful pre-program work, the VBA tests were disappointing. Completely satisfactory salt quenching, without re-ignition, occurred in only two VBA tests. These were accomplished with a quench charge ratio (QCR) of 0.023 lb salt per square inch of burning surface at dispersing charge ratios (DCR) of 13 and 28 lb of salt per lb of explosive. In both tests there was 6 inches distance from salt charge to initial burning surface.

Candidate materials for insulating salt charges from the rocket combustion environment were evaluated in firings of 5-inch-diameter, uncured end-burner motors. A pressed, alumina ceramic fiber material, Refractory Products Co. WRP-X-AQ, was selected for further evaluation and use in the final demonstration motor.

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*See References, Section 5.0

An 18-inch-diameter, heavyweight motor was designed for the final demonstration test. The motor approximated a one-half scale version of the two-pulse, STAR 37D preliminary design except that design operating pressure was maintained at 600 psi. The 18-inch motor mounts two insulated salt quench assemblies in its combustion chamber: (1) a cylindrical salt charge in the propellant grain cavity supported by an aluminum mandrel attached at the case head end, and (2) a conical salt charge mounted on the motor aft closure and surrounding the submerged portion of the nozzle.

Scaled-down versions of these quench assemblies were evaluated in open-air tests and then in 60-pound, 8-inch-diameter motor firings. These tests showed the WRP-X-AQ insulator inadequate to protect the salt charges from the erosive effects of motor combustion for more than a few seconds. Replacing this material with TI-P-304, a mastic, phenolic-asbestos material, was shown unsatisfactory in a subsequent 8-inch motor test. These tests also showed the explosive charge for the aft-end quench assembly had to be reduced to a DCR of approximately 70 to avoid unacceptable damage to the motor nozzle upon quench initiation.

One 18-inch-diameter final demonstration motor was then static fired under simulated altitude conditions. During manufacture, the motor grain was machined to half-scale simulation of the internal grain surface configuration of the STAR 37D at approximately 20% web burnout. To avoid failure of the WRP-X-AQ insulation, the head- and nozzle-end quench assemblies were simultaneously initiated only 1 second after motor ignition. However, progressive failure of the insulation occurred before quench initiation. As a result, much of the salt was neither properly dispersed nor delivered to the burning surface, and motor termination did not occur.

Substantial additional investigation is required to demonstrate the feasibility of salt quenching large solid propellant rocket motors such as the STAR 37D. Effort should first be directed toward perfection of salt quench charge configurations and explosive systems which will deliver the quench material to the propellant grain in a reliable, reproducible manner. A major consideration in this effort must be the proper thermal protection of the charges during rocket motor operation.

2.0 TECHNICAL DISCUSSION

2.1 Laboratory Research and Bench Tests

The Research Phase of this program was concerned with defining the necessary operating variables for the application of a salt quench system to extinguish a burning solid propellant. Theoretical considerations concerned with halting the combustion process and general background data from previous propellant extinguishment studies were considered in defining the experimental approach to this problem. A laboratory approach was devised to approximate the conditions to be found in a full-scale operating rocket motor. In this manner, more rapid alteration of the experimental variables should be achieved and the more critical operating parameters defined so that the scale-up version of an operating rocket motor could be designed and fabricated with increased confidence.

2.1.1 Theroretical Considerations

2.1.1.1 Extinguishment Mechanism. One combustion termination technique for solid rocket motors is quenching by solid coolant injection. This technique employs an explosive discharge to pulverize and propel a highly endothermic salt onto the burning surface. An all-solid quench system employing a hydrated aluminum sulfate has successfully extinguished 8-pound test motors,[1] and the results indicate that the system can be designed to terminate larger motors.

Propellant extinguishment by water quench has been demonstrated in motors having propellant weights in excess of 18,000 pounds. However, a rigorous definition of the extinguishment mechanism is still not available. Three basic mechanisms have been proposed in order to correlate extinguishment data:

1) Depressurization - Rapid cooling of the combustion products causes a pressure gradient (dP/dt) high enough to effect extinction.[2]

2) Temperature Drop - Combustion gases are cooled, lowering the heat feedback to the propellant below that necessary to sustain combustion.[3,4]

3) Surface Blanketing - A stream of water impinges on the propellant surface, essentially "floating" away the flame front and subsequently blocks the transfer of heat from the combustion products back to the propellant.[5,6,7]

Combustion extinguishment by salt quench appears to involve both the temperature drop and surface blanketing concepts proposed for water quench. A schematic of a typical burning surface before and after salt dispersion is shown on Figure 1 to illustrate the proposed extinguishment mechanism. Under steady state combustion, the propellant surface flame zone is considered to have a thermal gradient, as shown in Figure 1a. Point A represents the initial conditioned temperature of the propellant. The curve ABC represents the temperature gradient established by the surface regression rate and the heat flux from the combustion zone. Point B represents the temperature point at which propellant decomposition begins. BC is a preheat zone and represents a region of partially vaporized and/or decomposed material and generally is quite thin. At Point C, all solids have been decomposed and dissociation has occurred; then the gases begin to migrate and react through the flame zone. The curve CDE represents the temperature gradient experienced in the flame zone, which may be rate- or diffusion-limited, depending upon the motor pressure. Point E represents the theoretical flame temperature of the combustion products.

After the salt has been dispersed onto the propellant surface, as shown in Figure 1b, it first acts as a blanket, blocking the transfer of heat from the flame zone into the propellant. This interrupts the combustion process at the propellant surface by terminating the generation of decomposition products. Secondly, the salt decomposes because of the high heat fluxes from both the propellant and the combustion gases. This highly endothermic decomposition process absorbs heat from both the preheat zone in the propellant and the combustion gases in the chamber. In addition, the water vapor produced during the dehydration of the salt acts as a coolant when mixed with the combustion gases. The accumulative effect of these processes is the rapid reduction of both the temperature and pressure of the gases in the motor chamber. Permanent extinguishment results if the quantity of salt per unit area is enough to remain on the propellant surface until the temperature of the propellant is reduced below the autoignition temperature.

2.1.1.2 Quench Material Selection. Combustion extinguishment of solid propellant in a rocket motor by means of injecting a chemical in solid form into the chamber has been investigated for at least 10 years. IR&D programs conducted by Thiokol in 1963 investigated the feasibility of extinguishing a rocket motor by injecting powdered materials such as carbon and boron into the chamber through a head-end injector.[8] During an operational test, pressure was momentarily reduced about 42 percent in a motor containing a 4-pound CP grain of aluminized propellant. However, the pressure rapidly returned to its equilibrium level and the motor continued to burn to completion.

Howard and Crowell[9] at the Navy Missile Center performed some early quench experiments using dry salt. Potassium bicarbonate ($KHCO_3$) in the form of "Purple K" fire extinguisher power and potassium bromide (KBr) were used in these tests.

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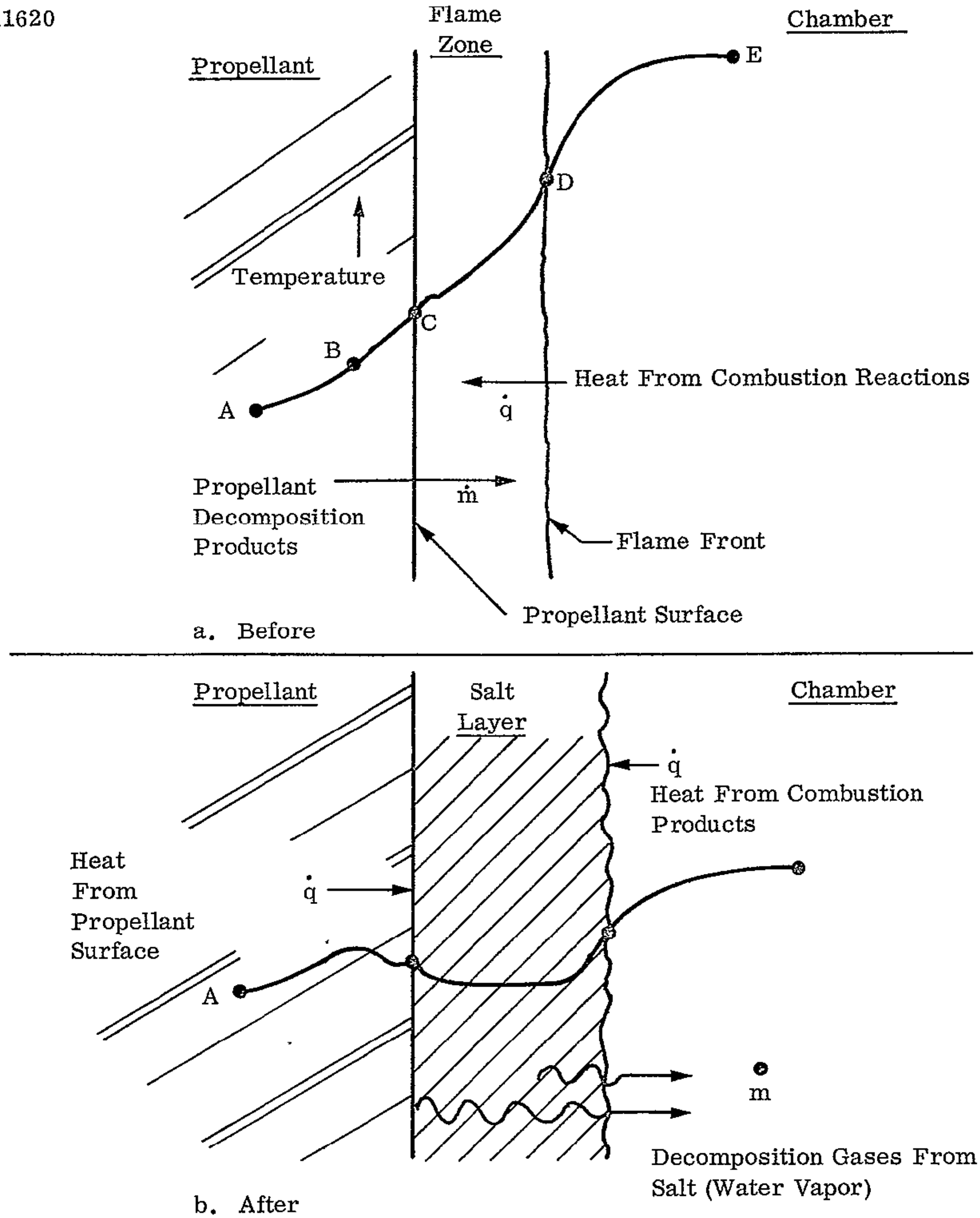

FIGURE 1. SCHEMATIC OF BURNING SURFACE BEFORE AND AFTER SALT DISPERSION

These salts were dispersed by gunpowder down the bore of 2.75-inch FFAR motors containing nonaluminized double-base grains. Several quenches were recorded, but the usual result was a pressure rise in the chamber. Reasons for the pressure rise appeared to be that the salt failed to thermally quench the chamber gases and, in addition, scoured the surface of the grain, resulting in an increase in the mass generation rate.

In IR&D experiments at Aerojet in 1964[2] and on NAS 8-11374[10] in 1965, the explosive discharge of a powdered coolant down the bore of a solid rocket motor behind an explosive-generated shockwave was investigated as a means of thrust termination. The shockwave never permanently extinguished combustion, but on several occasions one of the coolants, ammonium bicarbonate (NH_4HCO_3), prevented the aluminized PBAN-ammonium perchlorate propellant from re-igniting after it had been temporarily extinguished by a dP/dt depressurization. In all other tests, the powdered salt and gunpowder charge caused an increase in pressure due to the generation of additional decomposition produced such as ammonia, water vapor, and carbon dioxide.

In more recent tests conducted by Day and Bailey at Thiokol,[1] hydrated aluminum sulphate [$Al_2(SO_4)_3 \cdot 18\ H_2O$] was found to be as effective as water as a quenching medium. The heat required to dehydrate the sulphate (at about 87°C) plus the heat to vaporize the water of hydration were found to be enough to permanently extinguish combustion of an aluminized propellant in an 8-pound test motor. On Table I the heat absorbed during the decomposition of a gram of hydrated aluminum

TABLE I

HEAT ABSORPTION REACTIONS

SALT QUENCH

$$Al_2(SO_4)_3 \cdot 18\ H_2O\ (\text{solid}) \xrightarrow[\text{Heat}]{} Al_2(SO_4)_3\ (\text{solid}) + 18\ H_2O\ (\text{gas})\ (25^oC,\ 1\ \text{atm})$$

Heat to split off water	=	102 cal/gm
Heat to turn water to gas	=	285 cal/gm
Heat absorbed, total	=	387 cal/gm

WATER QUENCH

$$H_2O\ (\text{liquid}) \longrightarrow H_2O\ (\text{gas})$$

Heat to boil = 584 cal/gm

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sulphate is compared with the heat required to boil a gram of water. Although the heat per unit weight for salt is theoretically less than that for water (387 cal/gm versus 584 cal/gm at 25°C, 1 atmosphere), tests have shown that this compound is just as effective a quenchant as water on a weight basis. Hydrated aluminum sulphate has a crystal density of 1.69 g/cc and can be readily formed into desired shapes by pressure-molding, taking only 60 percent of the volume of water. More recent experience has shown that the hydrated aluminum sulphate can be dispersed more readily when compressed to a specific gravity of about 1.4, which occupies about 70 percent of the volume of water.

2.1.1.3 <u>Delivery Technique.</u> Early salt-quench experiments failed when gunpowder was used to propel the salt down the bore of the motor. The generated gases raised the chamber pressure, and an adverse pressure transient was produced. In addition, in the Aerojet experiments it is postulated that the flame from the gunpowder charge consumed some of the salt and possibly aided in sustaining propellant combustion. In tests performed by Thiokol,[10] the 12.5 grains of Mild Detonating Fuse (MDF) used to explosively disperse the salt generated no visible flame or gases and still powdered the pressed stick of salt. In more recent tests conducted by Thiokol, sheet explosives have also been successfully used for salt dispersion. Velocities of dispersion up to 5000 in./sec have been observed in some tests.

A review of previous salt quench tests also revealed that the location of the injector is critical. Early injector designs propelled salt from the forward end of the motor down the bore and parallel to the grain. Water quench tests performed on NAS 8-20219[5, 11] demonstrated that low angle impingement streams were lifted up by the propellant gases and were ineffective in extinguishing combustion. Strand has confirmed this in slab-burning window motor tests conducted at JPL.[12] Thiokol applied these observations by mounting the salt injector in the center of the port of a test motor from where the salt was exploded radially at the burning grain surfaces with impact angles ranging from 45 to 90 degress.

The fabrication techniques in these demonstration tests were based on experience from flare processing, in which powders were pressed into solid structures. By proper mixing of dry and damp salt, good cementing was achieved. In addition, fiber reinforcements were added for strength. Subsequent tests showed that this was not a necessity. The salt was pressed directly over the explosives, giving intimate contact and good shock propagation for powdering the salt to micron size. It appears that casting the salt could be advantageous with some of the candidates, if comparable pressed salt charge compaction and dispersal characteristics can be achieved.

2.1.1.4 Quench Requirements. The correlation of combustion extinguishment employing water quench has identified three distinct cooling requirements, which are summed to establish the total weight of quenchant. The water quench requirements in Table II show that the hot chamber gas requires about 2.5 pounds of water per pound of gas to drop the flame to 450°F. This is actually a function of gas composition, flame temperature, and temperature to which cooling is desired (below significant heat input to the propellant surface). Thermochemical computer programs are needed to take the calculations down to about 1,200°F; then steam tables are used to complete the computation as a function of chamber pressure.

TABLE II

WATER QUENCH REQUIREMENTS

Total $W_w = W_{wg} + W_{ws} + W_{wss}$

To Cool Hot Gases $\longrightarrow W_{wg} \cong 2.5$ lb H_2O/lb hot gas

To Quench Surface $\longrightarrow W_{ws} = (5 \times 10^{-6}) \dfrac{(A_b)\,(P_c)^{1.17}}{[\,(\Delta P_w)^5\,(\sin\alpha)]^{0.36}}$

To Prevent Re-Ignition $\longrightarrow W_{wss}$ = Small Continued Spray

Where:

A_b	=	Burn surface, sq in.
P_c	=	Chamber pressure, psia
ΔP_w	=	Water pressure - chamber pressure, psia
$\sin\alpha$	=	Sine of impact angle, spray jet/surface
W_w	=	Weight of water, lb
5×10^{-6}	=	Empirical constant

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Cooling the burning surface was found under NAS 8-20219[6] to be an exponential function of chamber pressure and a direct function of the impact velocity vector of the water jet. The denominator of the surface Quench (W_{ws}) on Table II shows this relationship as the square root of water differential pressure (pressure drop across the injector) times the sine of the impact angle, which is directly proportional to the impact velocity vector. The constant, 5×10^{-6}, incorporates terms to convert this term to velocity and also includes experimental efficiency.

Re-ignition in quenched motors can be prevented by providing residual coolant on the surface to counteract heat from hot hardware or subsurface binder chemical reactions. Choice of low radiation insulation materials and nozzle components, as well as careful attention to parts/grain view factors, is certainly important, but these factors can be alleviated by quench coolant covering their surfaces. This approach has to be traded off against ignition difficulties as it applies to two-pulse motor operation.

This discussion has assumed full efficiency in salt delivery. As with water sprays, mixing and heat transfer to the quenchant enroute to the grain are important, as is thermal diffusivity in the grain. Losses out the nozzle affect total efficiency, as does residence time for decomposition of salt in the hot gas; thus L* is an important parameter coupled with particle size. Another loss factor is possible ablation of the injector (salt material) before actuation. In Thiokol's feasibility tests, a "sacrificial layer" approach was used and appeared to work well for short burn times. Highly compressed salts form a hard crust, which seems to ablate much like good insulation. However, for long-firing duration motors, it will be necessary to insulate the quenchant charge with a frangible and ejectable insulation layer.

2.1.2 Background Investigations. Prior to this program, the principles discussed in the preceding section were applied to the extinguishment of three 8-pound (5-inch CP) motors: two TU-168 motors fired at Thiokol-Wasatch under ambient conditions and one TE-280 motor fired with a low back pressure in an altitude facility at Thiokol-Elkton. The salt quench charges were mounted in the center bore of the motors, with about 0.5 inch extending past the 45-degree tapered end of the cylindrical bore case-bonded grains.

One TU-168 test motor containing an 18-percent aluminized polyurethane grain with a relatively high pressure deflagration limit (P_{dl} = 12.5 psia) was permanently extinguished after burning 1.5 seconds at 240 psia. The injector deployed 1.2 pounds of salt, but 0.7 pound was recovered unused from the extinguished motor bore. Thus 0.5 pound was expended for 100 sq. in. of burning surface (0.005 lb/sq. in.), the same amount predicted for water quenching. Since aluminum sulphate has only 66 percent of the thermal efficiency of water, gains may have occurred due to the explosive dispersion and high velocity impact. Fluorescent dyes showed salt

embedded about 0.005 inch into the surface. This slight embedment could add sustained propellant cooling immediately after initial combustion termination, thus preventing subsequent spontaneous re-ignition.

The second TU-168 test motor used a 15-percent aluminum CTPB (ANB-3066) grain (P_{dl} - 0.5 psia) and was also extinguished after burning 1.5 seconds at about 250 psi; however, because of the very low P_{dl}, it re-ignited after 6.5 seconds and burned to completion. High-speed movies showed the termination transient (based on the exhaust plume) to be identical on both motors. Salt recovered from the forward end of this motor appeared to have compacted and ablated much like good insulation. The re-ignition also showed that a command restart after shutdown is feasible if sufficient heat can be delivered to the grain surface.

The TE-280 fired at simulated altitude conditions used a 16-percent aluminium, 86-percent total solids CTPB (TP-H-3062) propellant grain that was permanently extinguished after burning 2 seconds at 500 psia. The cell pressure in the test chamber at termination was 1.4 psia, which aided in preventing re-ignition of this propellant, which also has a low P_{dl} ($\sim$ 1.3 psia). The injector used in this test contained 0.94 pound of salt. Very little salt was recovered after the test; thus, it is assumed that the entire amount was expended in terminating 85 square inches of burning surface (0.011 lb/sq. in.). This is twice the amount per unit area consumed in extinguishing the polyurethane grain; however, the chamber pressure at termination was more than twice that present during the TU-168 test. This is in agreement with the expression developed for the water required for surface quench (W_{ws}) in Table II, which shows that the quantity of water required varies almost directly with chamber pressure.

During attempts to more fully understand the parameters concerned with the extinguishment of the propellant combustion, Thiokol conducted laboratory studies using a bench-scale testing device. This device was assembled as shown in Figure 2 so that the following parameters could be varied:

1) Injection force - the amount of explosive used per unit weight of the quench charge

2) Injection distance - the distance from the quench charge to the combustion zone

3) Composition of the quench charge

4) Quantity of the quench charge

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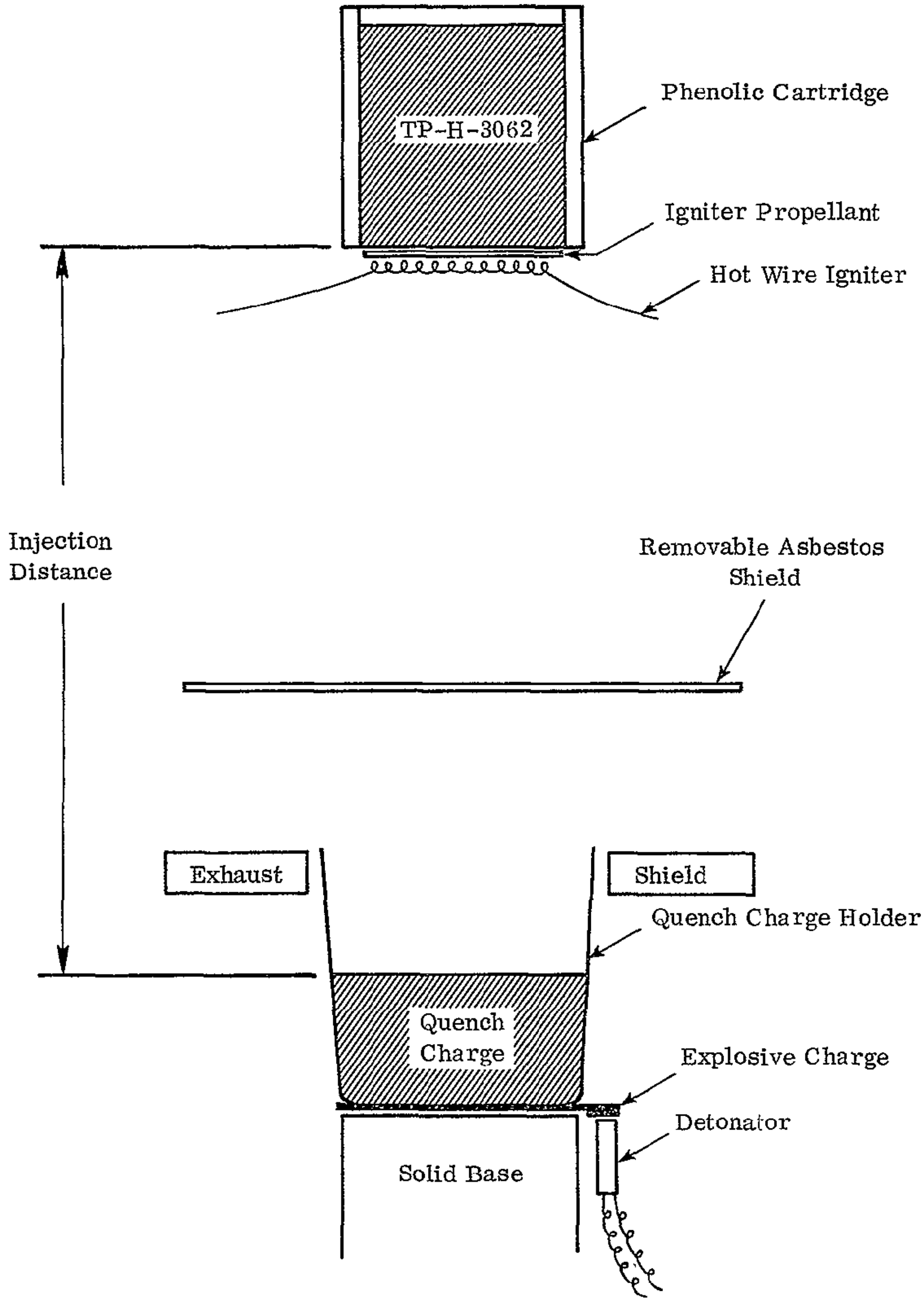

FIGURE 2. EXPERIMENTAL ARRANGEMENT FOR OPEN AIR QUENCH TESTS

The distance between the inverted propellant sample and the quench charge was controlled by the height of the propellant assembly. Using TP-H-3062 propellant in a paper phenolic cartridge, the total burn time was 30-32 seconds at atmospheric pressure. A removable shield was placed between the burning propellant and the quench charge assembly. This was removed immediately before the explosive charge was initiated. The quench charge was used in nonconsolidated form, resting on a polyethylene sheet in contact with the explosive charge. A separate exhaust shield was used to protect the Detasheet explosive from the flame.

The test assembly was used to evaluate charge weight/distance relationships for water, hydrated aluminum sulfate (48.6% water), and Arizona Road Dust (0% water). The last material is a known particle size silicate dust which should simulate an inert quench material. A standardized test was used by varying the amount of quench material and the distance from the burning propellant with the constant explosive charge initiated after 10 seconds of combustion. Tests were also conducted without quench material to confirm that the shock wave alone from the explosion would not quench the burning propellant.

As can be seen in Table III, the water is slightly more effective at a shorter injection distance for the same quench charge weight than the aluminum sulfate hydrate. Both of these are more effective on the same basis than the Arizona Road Dust. No assessment of the required amount of quench charge per unit area of propellant burning surface could be made in these tests due to the scattering of quench material past the propellant surface. Also, the ambient pressure combustion is easier to extinguish than elevated pressure combustion.

2.1.3 Experimental Approach. Based upon the theoretical considerations and the background investigations previously discussed, an experimental approach was formulated to obtain sufficient quantitative data on the salt quench approach to the extinguishment of TP-H-3062 propellant to permit design of successful subscale termination units. Design considerations required that the experimental program include the variables shown below. Ranges of each variable are shown for both the subscale and full-scale designs. These initially established ranges were adjusted somewhat during the course of the program.

TABLE III

RESULTS OF OPEN-AIR QUENCH TESTS USING VARIOUS QUENCH MATERIALS ON TP-H-3062 AT SELECTED QUANTITY AND DISTANCE LEVELS

Quench Charge Material	Quantity, grams	Injection Distance, inches 2	3	4	5	6	7	8	9
Water	0	0	°	0	°	°	°	°	°
	3	*	*	*	*	x	0	0/x	0
	5	*	*	*	x	x	x		
	7.5	*	*	*	*	*	*		
	10	*	*	*	*	*	*		
Aluminum Sulfate, Hydrated	0	0	°	0	°	°	°	°	°
	3	*	*	x	x	0	°	0	°
	5	*	*	x	x	x	0	0	°
	7.5	*	*	*	*	x	x	0	°
	10	x	*	x	*	*	*	x	
Arizona Road Dust	0	0	°	0	°	°	°	°	°
	3	*	*	x	0	0	°	°	°
	5	*	*	x	0	0	°	°	°
	7.5	*	*	*	x	x	0	°	°
	10	*	*	*	*	*	x	0	°

where 0 = Experimental nontermination
° = Assumed nontermination
x = Experimental termination
* = Assumed termination

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	Subscale Design	Full-Scale Design
Incidence Angle, degrees	0 to 60	Same
Standoff Distance, in.	3 to 10	To 20
Burning Duration, sec	5 to 20	To 45
Chamber Pressure, psi	300 to 700	Same
Dispersing Charge Ratio (DCR), lbm salt/lbm Detasheet explosive	1000/1 to 16/1	Same
Quench Charge Ratio (QCR), lbm salt/in.^{2} propellant surface area	0.003 to 0.015	Same

For the most part, the subscale ranges also satisfy the requirement for the full-scale motor, with the exception of an increase in the standoff distance limit to 20 inches and an increase in burn time to 45 seconds. Incidence angle is defined as the angle of deviation from a path normal to the propellant burning surface. In other words, a 0 degree incidence angle refers to a salt particle trajectory perpendicular to the burning surface.

A laboratory apparatus was devised to simulate the operating motor conditions and to vary the parameters of interest within the ranges specified above. The Vented Bomb Assembly (VBA) so constructed utilized an end-burning propellant (TP-H-3062) charge approximately 2 inches in diameter by 2 inches long ignited by a pyrogen igniter. Consolidated salt discs approximately 2 inches in diameter by up to 2 inches in length were housed in the opposite end of the VBA along with the explosive charge and initiator assembly necessary to disperse the salt and inject it onto the burning propellant surface. The exposed surface of the salt charge was covered by an insulator to protect it from the propellant flame front prior to initiation of the explosive charge. The entire VBA was housed within an altitude chamber with the nozzle sealed by means of a low pressure burst disc to allow propellant ignition while the VBA unit was exposed to altitude conditions. The variables intended to be examined in the VBA were:

Variable	Levels to be Investigated
Incidence Angle, degrees	0° to 45°
Standoff Distance, inches	3, 6, 12
Chamber Pressure, psia	300, 500, 700
Burning Duration, seconds	5, 10
Dispersing Charge Ratio, lbm salt/lbm Detasheet	10 to 600
Quench Charge Ratio, lbm salt/in.^{2} propellant surface area	0.01 to 0.05

The tests conducted in the VBA were designed to evaluate these variables in a set of experimental matrices shown in Table IV. These matrices were designed to provide the most logical and efficient approach to the definition of the operating parameters at the start of the investigation. However, alterations had to be made during these tests based upon the data obtained as discussed under VBA test results. For example, it was found that there was little, if any, effect in this test apparatus caused by the operating pressure and that the extended duration burning time was not a realistic variable within the framework of these laboratory tests.

In each of the tests designated in Table IV, data to be obtained were:

- Vacuum level of altitude chamber
- Motor operating pressure versus time
- Reduction of the pressure by the quench charge
- Termination or non-termination
- Dispersion of the salt charge
- Condition of unburned propellant (when termination occurred)

TABLE IV

VENTED BOMB ASSEMBLY TEST MATRICES

VBA TEST MATRIX I

Test Objective. Definition of Termination/Nonterminaton Boundary

Number of Tests 16

Test Constants

Propellant Charge	TP-H-3062 End-Burning Cartridge
Diameter, inches	1.9
Burning Duration, secs	5
Operating Pressure, psia.	500
Salt Charge, Diameter, inches	1 8
Incidence Angle, degrees	0
Standoff Distance, inches	6

Test Variables

Quench Charge Ratio (QCR) }
Dispersing Charge Ratio (DCR) } Salt Thickness (i.e, weight) Detasheet weight

VBA TEST MATRIX II

Test Objective: Effect of Standoff Distance

Number of Tests 16

Test Constants Same as VBA Test Matrix I except for standoff distance. Selected levels of QCR and DCR

Test Variables Standoff Distance, inches 3, 6, 12
(Note 6-inch distance tests run in Test Matrix I)

VBA TEST MATRIX III

Test Objective Effect of Operating Pressure

Number of Tests 4

Test Constants: Same as VBA Test Matrix I except for opeiting pressure. Selected levels of QCR and DCR

Test Variables Operating Pressure, psia 300, 500, 700
(Note fixed by nozzle throat size, 500 psia tests run in VBA Test Matrix I)

VBA TEST MATRIX IV

Test Objective Effect of Incidence Angle and Distance

Number of Tests 4

Test Constants Same as VBA Test Matrix I except for incidence angle and duration. Selected levels of QCR and DCR

Test Variables

Incidence Angle, degrees	0, 45
Duration, secs	5, 10

(Note 45° Incidence angle provided by obliquely cut propellant grain, therefore, larger burning surface Longer propellant grain provides longer burning time 0° angle and 5 secs duration tests run in VBA Test Matrix I.)

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Before the VBA tests were conducted, it was first necessary to define the type of salt quench charges to be used for proper dispersion and to evaluate the type of insulator to be used for protection of the salt charge from the flame front. These tests were also conducted on a laboratory scale using materials which had been previously proposed for incorporation into the subscale motor tests.

2.1.4 Preparation of Salt Quench Charges. The consolidated charges of aluminum sulfate octadecahydrate, $Al_2(SO_4)_3 \cdot 18H_2O$, were prepared by treating commercially available hydrated aluminum sulfate so that two forms were available: a "dry" form containing approximately 45 percent water [$Al_2(SO_4)_3 \cdot \sim 16\, H_2O$] and a "wet" form containing approximately 51 percent water [$Al_2(SO_4)_3 \cdot \sim 20\, H_2O$]. These forms were prepared by evaporating water from, or adding water to, the molten salt at 110°C. The melt was poured into aluminum foil trays, cooled, ground to pass a No. 30 screen, and analyzed for water content. A blend of these two forms in the calculated ratio to form the theoretical 48.6 percent water of the octadecahydrate was used in a steel mold to form the consolidated quench charges for these studies.

Previous investigations had used consolidated charges containing 0.5 percent of fiberglass fibers, pressed at levels up to 4000 psi. This type of charge was found to possess too much strength for proper dispersion of the salt by the Detasheet explosive as described under the open air fragmentation studies. Therefore, the fiberglass was eliminated and lower pressure forces were used for consolidation.

The technique developed for preparation of charges used in the VBA tests involved the blending of the hydrated salts in the "wet" and "dry" forms which will pass the No. 30 screen, on jar rollers for one-half hour. A preweighed quantity of the freshly blended material was placed in the 1.785-inch ID mold, the charge leveled, and the ram inserted. The pressure was increased rapidly to the 500-pound force level and maintained at that level for 2 minutes. In this manner, salt charges of from 15 to 60 grams in weight were produced with densities between 1.35 and 1.40 g/cc. A direct relationship was found between the density produced at 500 pounds force in the above die and charge weight used:

$$\text{density (g/cc)} = 1.412 - 0.001\ (\text{charge weight, grams})$$

It was also found that at a constant 70-gram charge weight, the density of the compacted cylinder formed in the above mold was a direct function of the logarithm of the force applied over the range of 50 to 1000 pounds force:

$$\text{density (g/cc)} = 0.367 \log (\text{force, lbs}) + 0.383$$

Above 1000 pounds force, the density more gradually approached the crystal density of the aluminum sulfate octadecahydrate (1.69 g/cc) with values varying from 1.51 to 1.66 g/cc for 70-gram charges compressed under loads of 1000 to 4000 pounds force. With fiberglass added to the powder, the densities ranged from 1.55 to 1.68 g/cc for the same charge weight and forces.

Based upon the dispersion results obtained with the type of salt quench charge prepared at lower compaction forces and without fiberglass and upon the fact that the subscale nozzle end salt quench charges were not designed to be a uniform thickness, the samples used in the VBA tests after the first three tests were all prepared at 500 pounds force (200 psi).

2.1.5 Insulator Studies. During previous investigations, an unprotected 450-gram $Al_2(SO_4)_3 \cdot 18H_2O$ solid quench charge in a 7-pound TP-H-3062 loaded motor was exposed to combustion chamber gases for 4.5 seconds at 500 psia. The total post-fire weight loss was 199 grams (43%). Approximately one-half of the total loss occurred during motor operation while the remainder of the hydrate was converted to the anhydrous state during the post-fire thermal soak. The anhydrous material deposited on the outer surfaces of the quench assembly was found to be brittle and flaky, but the hydrate substrate was unchanged from the prefire condition. As a consequence of these and other exposure test results, it was apparent that the salt-quench assembly should be insulated from chamber gases to preclude or minimize hydrate attrition.

Since one of the key factors in the termination mechanism is a thorough "blanketing" of the area between the propellant and the flame zone by the solid quench material, the insulation must be sufficiently frangible to avoid impairment of the quench material distribution at the propellant surface. The insulators are subjected to moderate erosion and char during motor burning, then shattered when the salt charge is exploded.

Candidate insulator materials for this application were:

1) Granulated natural cork in a phenolic resin system (Armstrong Cork 2755)

2) Asbestos phenolic (RPD 150)

3) Pressed ceramic fiber refractory material (WRP-X-AQ)

4) Paper phenolic, Grade 550

Samples of the candidate frangible insulation materials were exposed to the TP-H-3062 combustion environment in 5-inch-diameter, uncured end burner motor tests. Specimens of the consolidated aluminum sulfate hydrate were also mounted within the motor chamber in one test for a parallel evaluation of this material. These tests and their results are discussed in Section 2.4 of this report.

In the early VBA tests, discs of paper phenolic insulator were used to protect the Deta-salt quench assembly. Later VBA tests used the felt type of insulator that was selected for insulating the quench charge assemblies of the 8-inch and 18-inch motors. Discs of this felt material, Refractory Products WRP-X-AQ, were prepared for the VBA by splitting the 1/4-inch-thick material in half, applying the recommended hardener (HA) for this material, compressing it to an approximate 0.1-inch thickness between wire screens, and curing the material at 300°F for at least 24 hours. Semi-rigid, lightweight discs were obtained in this manner which could be trimmed to size with a knife so that a tight fit was obtained in the salt stick housing. The use of a quick-curing rubber composition (TA-L-309) bead around the edges of the insulator provided the flame front obturation found to be required to protect the Detasheet explosive.

2.1.6 Open-Air Fragementation Studies. One of the initial considerations concerning the injection of the salt quench charge was the dispersal of the salt by the explosive charge so that fine particle size material was injected rather than large solid chunks or a single cylinder. The charges prepared for the VBA tests were in the form of right cylinders, normally with an L/D considerably less than one. A cylinder of the salt charge was placed in direct contact with the Detasheet explosive. This material, which is a sheet explosive manufactured by E. I. duPont, consists primarily of PETN (pentaerythiritol tetranitrate) dispersed in an elastomeric binder. Nominal thicknesses of 10, 25, and 45 mil were available of the Detasheet D, which is 75% PETN and has a density of 1.45 g/cc and a detonation velocity of 7200 meters/sec. The Detasheet is normally initiated by means of a duPont E-106 E.B. cap, which has a base charge of 2.0 grains of PETN.

Initial tests made with salt quench cylinders prepared at high completion forces and using the fiberglass reinforcement material showed that the cylinders were ejected without appreciable dispersion. To solve this problem, a number of open-air firings were made with the salt sticks prepared under various compaction forces to produce a range of densities at various heights and with and without the fiberglass which had been used as a reinforcing aid. The effect of the shape, thickness, and weights of the Detasheet on the dispersal or non-dispersal of these salt sticks was measured by firing the various combinations in the salt stick housing at a taut polyethylene sheet at a set distance. Initially the distance was 15 feet; then this was reduced to 5 feet, when dispersal was achieved. Six matrices were evaluated, and the results are presented in Table V.

TABLE V

SUMMARY OF OPEN AIR-FIRINGS
DISPERSAL OF SALT STICKS USING DETASHEET

Test		Detasheet			Salt (1 18-Inch-Dia. Cylinder)			Dispersal		
Matrix	OA-	Shape	Thickness, mil	Weight, g	Compaction Force, lbs	Density, g/cc	Height, in.	No	Partial	Yes
I	1	O	9	0 50	3000	1.66	1.0	X		
	2	O	26	1 52	3000	1.66	1 0	X		
	3	O	9	0.48	2000	1 66	1.0	X		
	4	O	26	1.52	2000	1.66	1.0	X		
	5	O	9	0.49	1000	1.66	1 0	X		
	6	O	26	1.52	1000	1.63	1 0	X		
II	1	+	8	0.20	1000	1.52	1 1			X
	2	O*	8	0 50	1000	1.56	1 1		X	
	3	O	8	0 47	- loose	-	1.1			X
	4	+	25	0.54	1000	1.57	1 1			X
	5	+	45	0.92	1000	1 56	1.1			X
	6	O*	8	0 54	1000	1.51	1.1		X	
III	1	+	25	0.67	1000	1 51	1 1	X		
	2	+	45	1 11	1000	1.51	1.1	X		
	3	-	25	0.27	1000	1.49	1.1	X		
	4†	+	25	0.67	1000	1.50 †	1 1			X
	5	+	45	1 14	1000	1.56	1.1			X
	6	-	45	0 48	1000	1.50	1.1	X		
IV	1	+	8	0.16	2000	1.58	1.1	X		
	2	+	25	0.63	2000	1.59	1.1	X		
	8	+	45	1.23	2000	1.57	1.1	X		
	7	+	8	0.19	1000	1.48	1.1		X	
V	1	+	8	0.19	2000	1 60	0 5	X		
	2	+	25	0.65	2000	1.62	0 5		X	
	3	+	45	1 22	2000	1.61	0.5		X	
	4	+	8	0.19	3000	1.64	0.5	X		
	5	+	25	0.65	3000	1.64	0.5	X		
	6	+	45	1.23	3000	1.64	0 5		X	
VI	1	+	45	0.94	1000	1.50	1 1	X		
	2	+	45	0.98	800	1.44	1.2		X	
	3	+	7	0.14	600	1 41	1.2			X
	6	+	25	0.57	500	1.37	1.2			X
	4	+	7	0.15	200	1.21	1.4			X
	7	+	25	0.54	100	1.11	1.5			X
	5	+	45	0.97	50	1.02	1.7			X

*Plugs of Detasheet inserted into salt stick
† No fiberglass used in preparation of salt sticks in this and subsequent tests
Note: 1-inch height is nominal 70-gram salt stick
0.5-inch height is nominal 35-gram salt stick

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The results show that a lower density of the salt stick is required to achieve good dispersion of the salt and that a cross (+) of Detasheet is better than a circular disc (O). A single strip (-) of Detasheet tends to split the salt stick into two fragments rather than disperse it. Most important, other than the density, is the elimination of the fiberglass which had been used to reinforce the salt stick. Thus, the salt sticks fabricated for the VBA tests were prepared with densities on the order of the 1.4 g/cc, compacted under a force of 500 pounds.

2.1.7 Vented Bomb Assembly (VBA) Test Arrangement. The experimental arrangement of the VBA test apparatus is shown in Figure 3. Improvements were made to this end-on version to provide greater reliability of initiation of the Detasheet explosive. By rotating the detonator centerline 90° so that it was in line with the VBA centerline, the detonator contacted the Detasheet explosive in the center rather than at the edge. This in-line version change involved only the salt stick housing and its components. All other features of the VBA test apparatus are the same as shown in Figure 3.

Assembly of the VBA for a test involved loading the salt stick housing with the quench charge and the propellant housing with the propellant cartridge. These components were then attached to opposite ends of the VBA case to which the nozzle, burst disc, igniter, and pressure transducer were attached. The assembled unit was placed inside the altitude simulation chamber, which was evacuated to a level of 30 - 40mm pressure. The end-burning TP-H-3062 grain was ignited using a TE-P-621-02 pyrogen igniter. An electrical signal to the E-106 E.B. cap, 5 seconds after ignition, initiated the Detasheet explosive placed directly against the salt charge, which was covered by the insulator.

Alignment of the detonator and direct contact with the Detasheet explosive were found to be quite critical. Using the in-line model salt stick housing, the detonator extended through the aluminum witness plate upon which the Detasheet explosive was placed. This witness plate provided a flat rigid surface for the Detasheet, an alignment tool for the detonator, and an expendable witness plate to accept the explosive charge as evidence that the explosion had propagated throughout all of the preweighed explosive sheet. An imprint of the Detasheet sample used was made on the witness plate and this was examined after each VBA test to document the amount of explosive actually used during the test. Various configurations of the Detasheet were used,including full circles, cruciforms (crosses) and circles from which smaller circles had been cut to adjust the weight of explosive. The weight of explosive to be used in a test was determined by the weight of the salt charges used and the desired Dispersant Charge Ratio (DCR), expressed as pounds of salt per pound of Detasheet.

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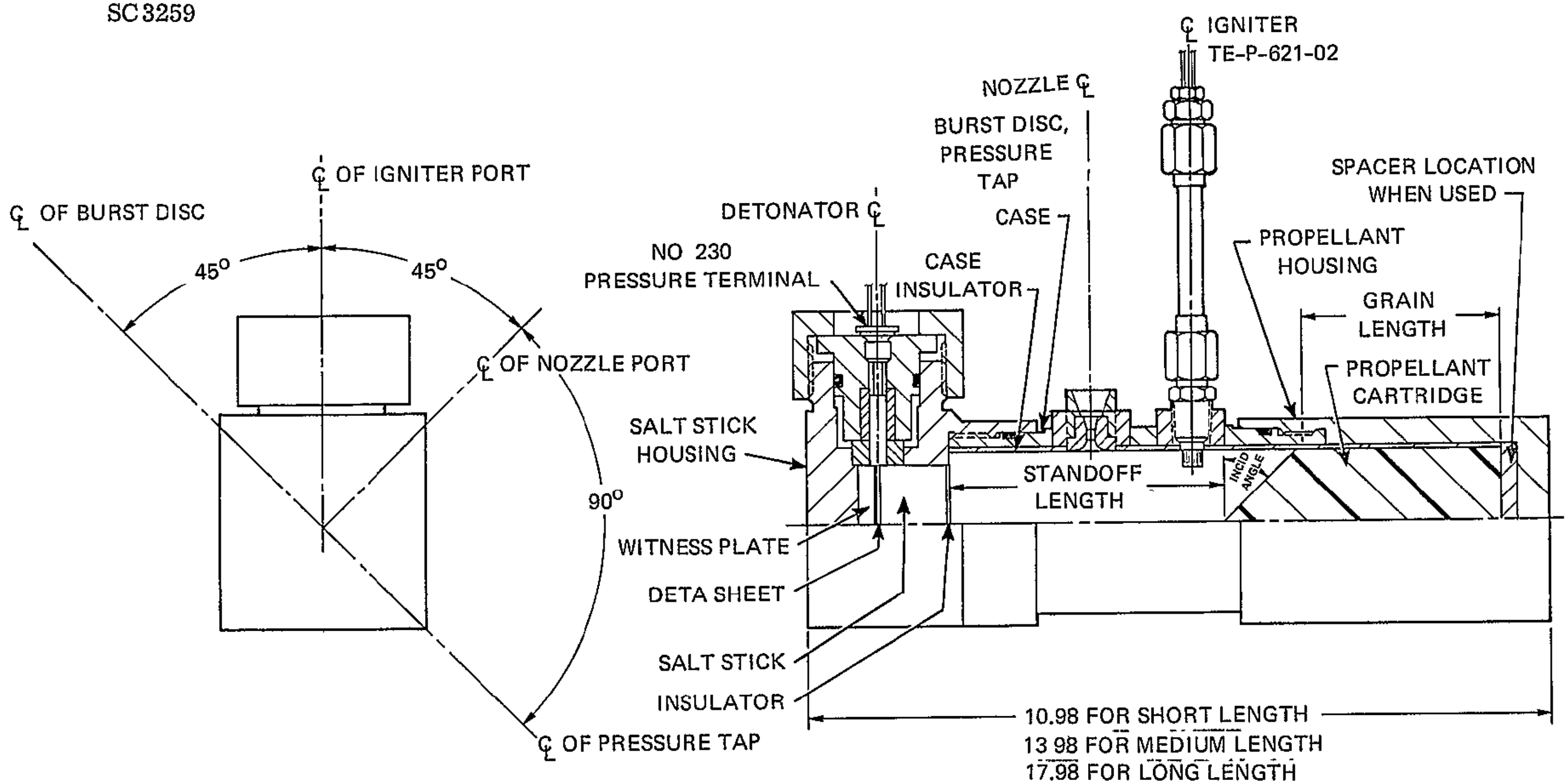

FIGURE 3. VENTED BOMB ASSEMBLY
(VBA) END-ON VERSION

Soft bushings of rubber and expanded polystyrene were used for further alignment of the detonator assembly within the detonator holder and to attenuate the shock wave of the detonator so that the holder would not be cracked on initiation of the E106 E.B. cap. An aluminum back-up washer had to be used in the in-line model to prevent the detonator from being pushed down below the level of the witness plate during combustion, out of contact with the Detasheet explosive.

The salt charge to be used in a test was prepared as described in Section 3.1.4 with the weight determined by the desired Quench Charge Ratio (QCR). This was expressed as the pounds of salt per square inch of propellant burning surface exposed during the test. Normally the salt charges used were right cylinders with a diameter of 1.780 inch and lengths of less than one inch. Certain specimens were also prepared to accept a ramp of the explosive for explosive configuration studies. The salt charge was placed in direct contact with the Detasheet explosive and covered on the other end of the cylinder by an insulator disc prepared from either paper phenolic (Grade 550) or WRP-X-AQ felt. This entire assembly was seated within the socket of the salt stick housing and the edges of the insulator disc were covered with TA-L-309, a quick curing polysulfide composition. The fillet of rubber so formed prevented the propellant flame from reaching the Detasheet to consume it before it could be initiated by the E106 E.B. cap.

Cartridges of TP-H-3062 propellant were prepared by machining right cylinders of cured propellant to provide 2.76 square inches of end-burner surface and cutting to length to provide 8.5 seconds of burning time. These grains were potted into paper phenolic tubes using a room-temperature-curing TA-D-309A epoxide composition. For the 45-degree incidence angle tests, longer grains were potted into the paper phenolic tube and the 45-degree angle was machined on the entire cartridge end-burner surface. This provided a 5.26-square-inch propellant end-burner surface. These cartridges were slip fit into the propellant housing along with the appropriate spacers required to adjust the propellant surface to the proper standoff length.

Three different lengths were available for the VBA case to allow for the various standoff distances to be evaluated. Each of these cases could be used for the shorter standoff distances by the proper selection of spacers behind the propellant cartridge. The metal case was lined with a paper phenolic insulator, which also provided the support for the propellant cartridge at the desired standoff distance. Holes were drilled through this insulator to match the ports in the case for attachment of the nozzle, burst disc, igniter, and pressure transducer. A 2-mil saran burst disc was bonded into the nozzle assembly so that the VBA was a sealed unit when placed inside the altitude simulation facility. This burst disc remained intact during evacuation of the altitude chamber but ruptured on ignition of the propellant grain by the pyrogen igniter. The TE-P-621-02 pyrogen igniter consisted of a small CP grain of non-aluminized propellant ignited by a squib and boron pellet initiator, which

served to pressurize the VBA chamber and ignite the surface of the TP-H-3062 propellant grain. An angled port on the igniter directed the flame front to the surface of the propellant cartridge. For the longest standoff distance, the igniter port was sufficiently far from the propellant surface so that an ignition aid on that surface had to be provided in the form of low-ignition, fast-burning propellant strips.

The assembled VBA unit was mounted in a chain vise inside the altitude chamber and the electrical connections were made for the pyrogen igniter, the detonator, and the pressure transducers. Multiple pressure transducers were used in some of the tests to measure both the operating pressure of the VBA during combustion and the low pressure ranges during pump down and after quench of the combustion. Five seconds after the pyrogen igniter was fired, the detonator was initiated to discharge the salt quench charge against the burning propellant surface. If quench was achieved, the pressure was reduced and combustion ceased. Otherwise, the combustion resumed and the propellant continued until burnout of the cartridge. Removal and disassembly of the VBA allowed examination of the components for quench of the propellant grain, dispersal of the salt, and proper operation of the Detasheet as shown by the witness plate. Data reduction of the firing trace produced by the pressure transducer showed the vacuum level in the altitude chamber and the VBA chamber pressure during the entire operation. Removal of the debris from the VBA chamber allowed measurement of the degree of dispersion of the salt after separation from the char of the insulator.

2.1.8 Vented Bomb Assembly (VBA) Test Results. Using the VBA test arrangement as described in the previous section, a total of 68 tests were conducted in both versions of the VBA. A greater degree of reliability of initiation of the Detasheet explosive was achieved using the in-line version (69 percent versus 47 percent for the edge-on version). Overall, 57 percent of the tests involved initiation of the Detasheet explosive, but only 32 of these were applicable for correlation within the four experimental matrices established for this investigation. Numerous experimental difficulties such as burst disc and pyrogen tube failures precluded full definition within these matrices. A summary of the tests run, categorized by the results obtained, is shown in Table VI. The experimental conditions and measured results on all of these tests are summarized in Appendix B. Simplified summaries of these data are presented within this section for correlation of data corresponding to each of the experimental matrices.

During these tests, the pressure within the VBA after quench initiation was reduced to zero in nine of the units. However, four of these involved a burst disc rupture simultaneous with the quench charge initiation. The attendant rapid depressurization would normally be sufficient to extinguish the propellant, and this was found to be the case in all but one of these four tests. Three of the five remaining

TABLE VI

SUMMARY OF VBA TESTS RESULTS

Detasheet Initiated	Burning Propellant	Why Not?	Pressure Reduction	Reignition to Burnout	VBA Version Edge-on	VBA Version In-line	No. of Units	Remarks
No	Yes	Detasheet burned	-	-	x		9	Out of 36 edge-on version units
		Det not in contact	-	-	x		10	
		Det not in contact	-	-		x	6	
		No firing signal applied	-	-		x	2	Out of 32 in-line version units
	No	Det not in contact, no grain used	-	-		x	2	
Yes	No	No grain used	-	-	x		3	
						x	1	
		Grain not ignited, under vacuum	-	-	x		3	
	Yes	-	Partial	Yes	x		8	
						x	15	-
		-	To 0 psi	Yes	x		2	
						x	1	
						x	1	Burst disc went
		-	To 0 psi	No	x		1	
						x	1	
						x	3	Burst disc went

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units exhibited a 100-percent drop in pressure but reignited to allow the propellant cartridge to burn out. These units utilized QCR levels of 0.012 and 0.017 lbs salt/in.^{2} propellant and DCR levels of 13 and 28 lbs salt/lb Deta. Only two of the tests exhibited complete quench (i.e., no reignition of the propellant) without rupture of the burst disc, and these occurred at a QCR level of 0.023 lbs salt/in.^{2} propellant with DCR levels of 13 and 28 lbs salt/lb Detasheet. These results will be discussed further in conjunction with the experimental matrices.

Good dispersion of the salt charges in open air was previously shown to involve mainly the reduced density of the charge (i.e., lower consolidation forces) and the elimination of the reinforcing fibers. When used in the VBA tests or in final form in the subscale motor tests, an insulating layer is required on the exposed surface of the salt charge. Tests of the ability of the explosive charge to disperse the salt were conducted initially within the VBA pressurized to 700 psig with dry nitrogen. A measurement of the degree of dispersion was obtained by collecting the debris within the VBA after initiation of the Detasheet explosive and weighing that quantity which would pass through a No. 30 sieve (%-30), that is, the amount of material which was returned to the original form from which the salt charges were prepared.

Without an insulator present, the salt charge could be dispersed to greater than 90 percent of the original form. However, this fraction was reduced by the presence of an insulator, as shown in Table VII. The thinner paper phenolic insulation allowed better dispersion. Slightly reduced dispersion was produced by the felt (WRP-X-AQ) insulation, but this insulator was also present as a thicker disc. It is interesting to note that the E106 E.B. cap (det) alone produces a significantly reduced degree of dispersion, as might be expected from the reduced and more localized explosive force. This explains the minimal pressure reductions experienced in the operating VBA units which failed to achieve initiation of the Detasheet explosive.

Similar results were obtained in complete VBA units, including the propellant cartridge in place at a 6-inch standoff distance. Using a paper phenolic insulation bonded to the salt charge, less than half of the salt was dispersed to its original form against the nonburning propellant grain even though a significant explosive charge was used (DCR=7). This was further reduced with a decrease in explosive charge. Significantly poorer dispersion was found when a notched salt charge was used at an intermediate DCR level. In this case (VBA No. 26), the cylindrical salt charge had been cut in half so that it could accept a ramp of layered Detasheet strips. This appreciably weakened the cylinder so that it fragmented into larger chunks rather than be redispersed into the original powder.

TABLE VII

EVALUATION OF SALT DISPERSION IN THE VBA TEST APPARATUS

Condition	VBA No.	DCR, lbs Salt / lb Deta	Salt		Detasheet				Insulator		Residue, %-30
			Thickness, inch	Density, g/cc	Form		Initiation		Type	Thickness, mil	
					Cross	Disc	Edge	Center			
700 psig	10	25	0.53	1.38	x		x		None	-	92
Dry N_2	11	27	0.54	1.33	x		x		Phenolic	60	71
Pressure	12	28	0.55	1.34	x		x		Phenolic	15	80
(No propellant	45	10	0.49	1.47		x		x	WRP-X-AQ	77	60
charge)	43	Det only	0.54	1.34					WRP-X-AQ	93	30
Non-firing	28	7	0.25	1.37	x	x	x		Phenolic	15	44
Units	26	13	0.50*	1.39		x	x		Phenolic	15	9
(Propellant	30	29	0.50	1.40	x		x		Phenolic	15	29
charge)											

*Salt charge was notched to accept ramp of Detasheet

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Direct comparison of the residue measurements for the nitrogen pressurized tests and the non-burning propellant tests is probably not completely justified based upon a comparison of shock wave propagation at atmospheric and elevated pressures. It would be more likely that the shock wave under elevated pressure would have a greater shattering effect on the salt charge than it would with only atmospheric pressure applied to the surface of the salt charge.

The effect of the propellant combustion within 6 inches of the surface of the quench charge assembly was found to be minimal under the desired operating conditions. A quarter-inch-thick salt charge in contact with a 25-mil-thick Detasheet disc and covered with a 75-mil-thick WRP-X-AQ insulator disc was exposed to the flame of the TP-H-3062 propellant for 8 seconds, during which the pressure rose progressivley from 420 to 730 psia (VBA No. 46). On disassembly, the quench assembly was found to be intact with only the insulator charred but still adhering to the salt charge. Both the salt charge and the Detasheet disc were intact and without evidence of flame exposure. The use of the TA-L-309 rubber fillet around the edges of the insulator prevented the flame front from reaching the salt charge or the Detasheet explosive disc.

At a lower pressure level, some effect on the quench assembly was found. When a one-half-inch-thick salt charge in contact with a 25-mil-thick Detasheet disc and covered with a 130-mil-thick WRP-X-AQ insulator disc was exposed to explosive decompression then propellant burning for 9.2 seconds, some degradation at the salt-insulator interface was found. In this case (VBA 67), overpressurization of the VBA unit occurred on ignition due to the presence of solvent vapors from a nitrocellulose glue used to adhere a starter propellant to the TP-H-3062 grain. This caused the rupture disc to burst at 1700 psi and resulted in progressive burning at 20 to 110 psia for 9.2 seconds. The standoff distance in this case was 12 inches. After disassembly, the insulator was found to have separated from the salt charge surface on one side so that the salt was partially foamed (dehydrated) in that area. Otherwise the quench assembly was intact, including the Detasheet disc below the salt charge.

These tests showed that even under the more drastic combustion conditions, the quench assemblies used in these VBA tests could withstand the environment of the propellant combustion so long as the insulator disc remained intact and the flame front could be prevented from reaching the Detasheet explosive. The Detasheet explosive would not explode when in contact with the flame front but merely burned. At 700 psia, this material was found to have a burning rate of 0.07 in./sec. Thus, in less than 2 seconds after exposure to a flame, sufficient explosive sheet could be consumed (~ 1/8 inch) to prevent contact with the initiator (det) and dispersal of the salt charge.

Test Matrix I was designed to establish a relationship between Quench Charge Ratio (QCR) and Dispersant Charge Ratio (DCR) at constant pressure, duration, standoff distance, and incidence angle. Results of the VBA tests in which propagation of the Detasheet explosive had occurred and which fit the constants set for Matrix I are shown in Table VIII. Here five QCR levels were selected with various DCR levels for each. The target constant pressure was not maintained during these tests but varied from 200 to 700 psi. For the purposes of the comparisons within Matrix I, it was assumed that the pressure had little, if any, effect. Confirmation of the extent of this effect was obtained in Matrix III (Table X) where only limited effect could be seen for higher pressure at the larger QCR values.

Within Matrix I, a relationship can be seen of increased percent reduction of pressure with decreasing DCR values at constant QCR levels of greater than 0.017. However, there is an apparent reversal of this relationship at the lower QCR levels. As far as can be determined from these data, no discernible effect is caused by orientation of the E106 detonator as long as initiation of the Detasheet explosive is obtained. The form or shape of the explosive also does not appear to have a large bearing on the ability of the salt charge to quench the burning propellant, as long as complete propagation of the Detasheet explosive is obtained.

Only two of these tests (VBA Nos. 13 and 41) provided full quench of the propellant combustion by reducing the chamber pressure by 100 percent and preventing reignition of the quenched grain. However, similar tests using opposing explosive forms and initiator orientations did not duplicate the same pressure reduction values and the combustion continued to burn out. Complete reduction of the chamber pressure could be achieved at the same two DCR values with about one-half the QCR level, but insufficient salt appeared to be present for the quench to be sustained. In both of the latter cases (VBA Nos. 16 and 18), the propellant reignited and burned to completion.

The complete set of data obtained for Matrix I during this investigation, including those tests which involved incomplete propagation of the Detasheet explosive, is presented in graphical form in Figure 4. Here it can be seen that the best reduction in pressure, and thus the highest probability of obtaining a complete quench, occurred at QCR levels between 0.011 and 0.023 lbs salt/in.^{2} propellant and at DCR values of 30 or less. Based upon these data, those values were used to select the parameters for Matrices II (Table IX) and III (Table X) along with the constant 5-second duration and a target operating pressure of 500 psia.

TABLE VIII

CONDITIONS AND RESULTS OF VBA TESTS FOR MATRIX I (QCR VS DCR)
6 inch Standoff Distance, 0° Incidence Angle,
5 seconds Duration to Quench Singal

							Results					
	Conditions						Pressure		Time to			
	QCR,	DCR,	Detasheet				At Quench		Minimum	Reignition		
	lbs Salt	lbs Salt	Form		Initiation		Signal,	%	Pressure,	To Burnout		
VBA No.	in.^{2} Prop.	lb Deta	Cross	Disc	Edge	Center	psia	Reduction	secs	Yes	No	Notes
52	0.011	7		x		x	520	85	0.7	x		
37		13		x		x	530	97	1.0	x		
16		14	x		x		710	100	1.3	x		
18		27	x		x		670	100	1.0	x		
65		29		x		x	725	73	0.5	x		
66	0.017	7		x		x	525	84	0.8	x		
47		10		x		x	540	90	0.8	x		
61		14		x		x	475	90	0.8	x		
63		29		x		x	345	91	1.1	x		
41	0.023	12		x		x	540	100	1.6		x	
33		13	x	x	x		520	83	0.5	x		1
13		27	x		x		580	100	1.0		x	
38		28		x		x	570	78	0.7	x		
14		57	x		x		720	94	0.8	x		
20		77	x		x		685	59	0.5	x		
15		165	x		x		570	25	0.1	x		2
27	0.034	13	x	x	x		210	64	0.4	x		
42		14		x		x	660	90	0.9	x		
40		27	x		x		520	67	0.4	x		
25		159	x		x		680	9	0.3	x		3
32	0.045	58	x		x		540	74	0.6	x		
36		87	x		x		585	68	0.5	x		
17		540	x		x		610	59	0.2	x		3

Notes: (1) Possible nozzle blockage after quench caused pressure to rise, then fall, before reignition to burnout.

(2) Questionable Detasheet initiation

(3) Only partial Detasheet initiation; DCR value corrected for amount indicated by witness plate.

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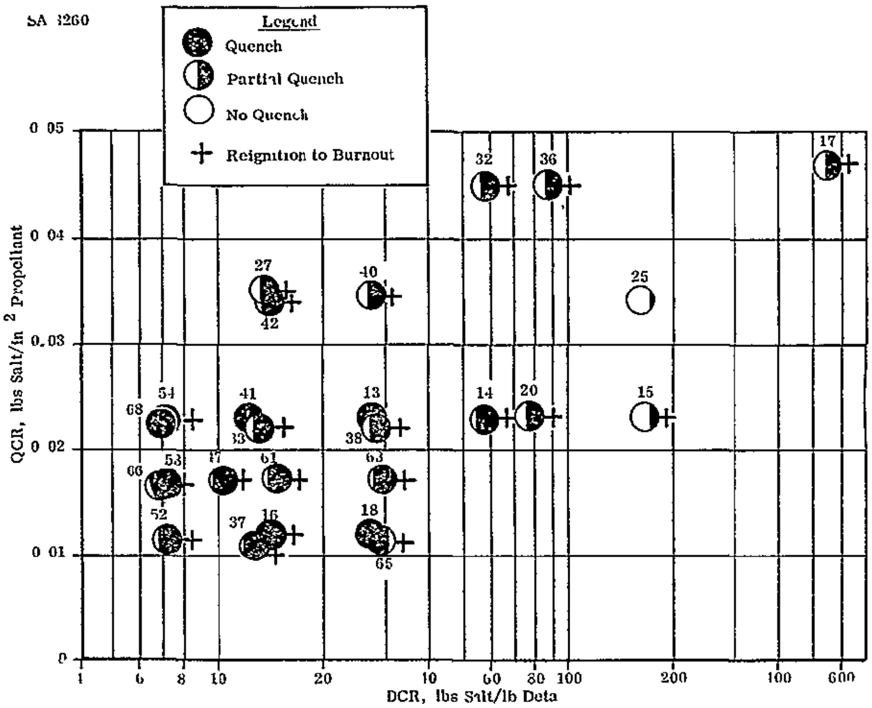

FIGURE 4. CORRELATION FOR VBA TEST MATRIX I

To evaluate the effect of standoff distance, the Matrix I constant value of 6 inches was doubled in the Matrix II tests using a constant QCR value of 0.023 lb salt/in.^{2} propellant with DCR values of 7, 13 and 27 lbs salt/lb Detasheet. Results of these tests are correlated in Table IX with the corresponding Matrix I VBA tests using a 6-inch standoff distance. The extended distance through which the salt must travel to reach the burning propellant surface appears to cause a lower reduction in pressure and results in a nonquench situation. However, duplicate tests at the 6-inch standoff distance resulted in sufficient variation to bracket the results obtained from doubling the standoff distance. Thus, there appears to be little, if any, effect caused by the standoff distance within the 6- to 12-inch range.

Pressure also does not appear to affect the ability of the quench charge to reduce the pressure and to provide a quench of the burning propellant. Only limited effects are evident in Table X with what appear to be reversals at the highest and lowest QCR levels presented.

The principal parameter to be evaluated in Matrix IV, the incidence angle, required that an inclined propellant surface be exposed to the salt being dispersed. To evaluate a large incidence angle, a 45-degree value was selected and a QCR level of 0.017 lbs salt/in.^{2} propellant was used. This level is provided by a 0.5-inch-thick salt stick in the VBA as opposed to a 0.38-inch-thick salt stick for 0-degree

TABLE IX

CONDITIONS AND RESULTS OF VBA TESTS FOR MATRIX II
(STANDOFF DISTANCE VS DCR)
QCR = 0.023 lbs Salt/in.^{2} Propellant, 0° Incidence Angle,
5 seconds Duration to Quench Signal

Conditions							Results					
			Detasheet				Pressure		Time to Minimum Pressure, secs	Reignition To Burnout		
			Form		Initiation							
VBA No.	DCR, lbs Salt / lb Deta	Standoff, inches	Cross	Disc	Edge	Center	At Quench Signal, psia	% Reduction		Yes	No	Notes
54	7	6	x	x		x	780	100	0.6	x		1
68		6		x		x	510	100	0.3		x	1
59		12		x		x	520	65	1.6	x		2
41	13	6		x		x	540	100	1.6		x	
33		6	x	x	x		520	83	0.5	x		2
57		12		x		x	480	96	1.5	x		
13	27	6	x		x		580	100	1.0		x	
38		6		x		x	570	78	0.7	x		
55		12		x		x	370	88	1.5	x		

Notes (1) Rapid pressure venting (-dp/dt) due to rupture of burst disc or pressure terminal.

(2) Possible nozzle blockage after quench caused pressure to rise, then fall, before reignition to burnout.

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TABLE X

CONDITIONS AND RESULTS OF VBA TESTS
FOR MATRIX III (EFFECT OF OPERATING PRESSURE)
0° Incidence Angle, 5 Seconds Duration to Quench Signal,
6-Inch Standoff Distance

QCR, lbs Salt / in ^{2} Prop.	DCR, lbs Salt / lb Deta	VBA No	Pressure: At Quench Signal psia	Pressure: % Reduction	Time To Minimum Pressure, secs	Reignition To Burnout: Yes	Reignition To Burnout: No
0.012	13	37	530	97	1.0	x	
		16	710	100	1.3	x	
	28	18	670	100	1.0	x	
		65	725	73	0.4	x	
0.023	13	33	520	83*	0.5	x	
		41	540	100	1.6		x
	28	55	370	88	1.4	x	
		38	570	78	0.7	x	
		13	580	100	1.0		x
0.035	13	27	210	64	0.4	x	
		42	660	90	0.9	x	

*Possible nozzle blockage after quench caused pressure to rise, then fall, before reignition to burnout.

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TABLE XI

CONDITIONS AND RESULTS OF VBA TESTS FOR
MATRIX IV (INCIDENCE ANGLE VS DCR)
QCR = 0.017 lbs Salt/in.^{2} Propellant, 6-inch Standoff
Distance to Center of Surface, 5 Seconds Duration
to Quench Signal, Detasheet in Disc Form with
Det Against Center of Disc

Conditions: VBA No.	Conditions: DCR, lbs Salt / lb Deta	Conditions: Incidence Angle, degrees	Results: Pressure: At Quench Signal, psia	Results: Pressure: % Reduction	Results: Time to Minimum Pressure, secs	Results: Reignition Yes	Results: Reignition No
66	7	0	525	84	0.8	x	
60	7	45	520	50	0.5	x	
47	10	0	540	90	0.8	x	
64	10	45	515	98	1.0	x	
63	29	0	345	91	1.1	x	
56	28	45	455	100	1.0	x*	

*Reignition did not occur until greater than 10 seconds after chamber pressure reached 0.

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incidence angle. Three tests were made of this effect, as shown in Table XI. Here the first observation is that a considerable decrease in pressure reduction is obtained on increasing the incidence angle at a low DCR value (7). However, at a higher DCR value (28), complete reduction in operating pressure is obtained and the burning propellant remains extinguished for greater than 10 seconds before reignition. The intermediate DCR level (10) also provides a greater reduction in pressure at the higher incidence angle.

Thus, it would seem that the larger dispersal forces (low DCR values) could cause some problems at high incidence angles and at greater standoff distances. It would probably be better to design for less explosive charge to disperse the salt which has only the minimum strength required for moderate mechanical handling. The general conclusions which can be drawn with respect to the salt quench assembly based upon these investigations are as follows:

1) The salt charge density should be on the order of 1.4 specific gravity and should be prepared without the use of reinforcements and without cutouts which could cause fragmentation rather than dispersion.

2) The Detasheet explosive must be protected from the flame front.

3) The Detasheet explosive is not affected by pressure alone up to 700 psia.

4) Alignment and/or contact of the initiator (E106 E.B. cap) with the Detasheet explosive is mandatory to assure initiation.

5) Continuity of the Detasheet explosive in the area of contact with the initiator is quite important but does not have to be continuous in all directions in other portions of the explosive.

6) The QCR level should be on the order of 0.02 lb salt/in.^{2} of propellant surface.

7) The DCR level should be on the order of 12 lb salt/lb of Deta but not lower.

8) Operating pressure of the motor does not seem to affect the quench results within the range of 400 to 700 psia.

9) No disadvantage is incurred with an incidence angle of up to 45 degrees.

10) The effect of the quench charge on the burning propellant does not change between 6 and 12 inches.

These conclusions are ranked in order of decreasing certainty of support by the results obtained but are all felt to be certain enough so that further work in this area can be based upon them.

2.2 Preliminary Full-Scale ATTA Motor Designs

At the outset of this program, preliminary designs for a two-pulse, single-quench motor and a two-pulse, double-quench motor were prepared. These designs are described in Appendix B.

2.3 Test Vehicle Design

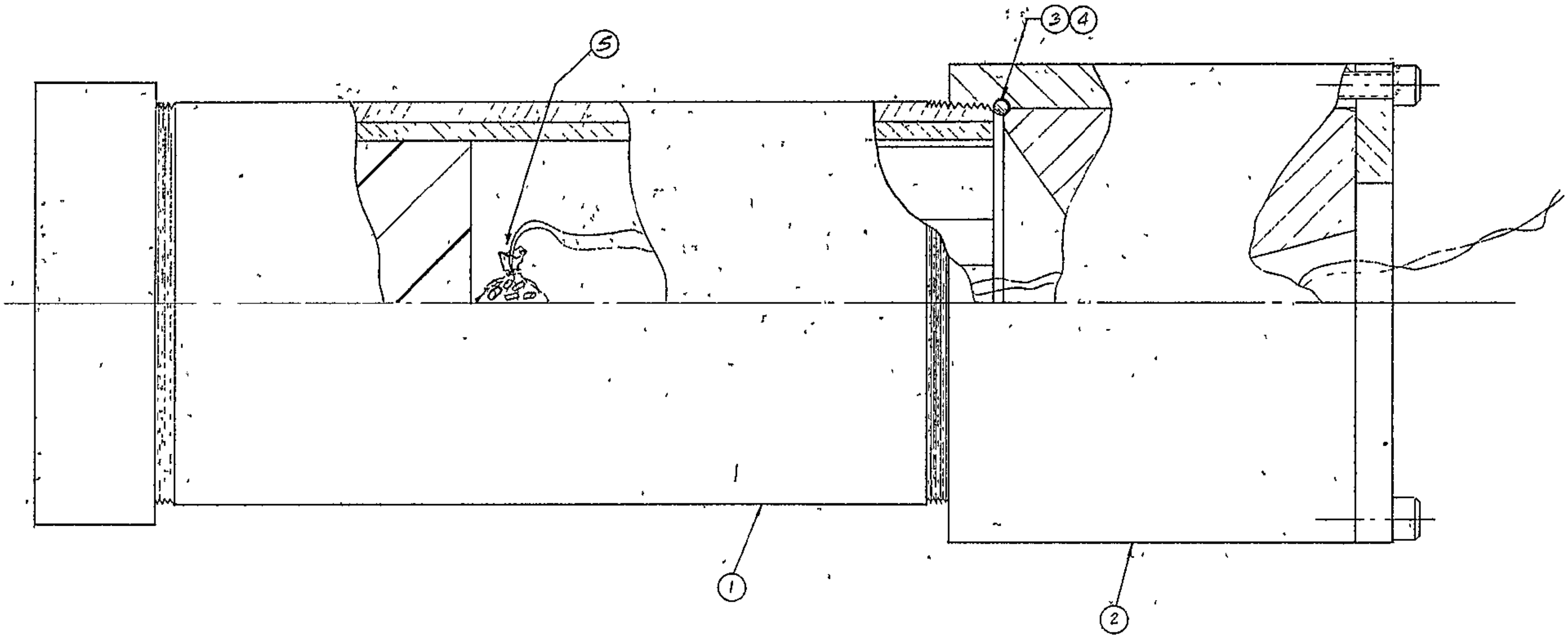
The results from the VBA test and the 5-inch CP tests were reviewed to determine a QCR and DCR that would quench the motor without causing excessive scouring, pitting, and gauging of the propellant surface and excessive pressures in the motor cavity. The table below summarizes the DCR and QCR from the three successful quenches of TP-H-3062 propellant.

Test Vehicle	QCR	DCR
VBA No. 41	0.012	13
VBA No. 13	0.012	28
5-inch CP, PV-00525	0.011	12

It is apparent from the 5-inch CP tests that low DCR's will cause undesirable surface effects to the propellant surface, which could cause high reignition pressures in the motor due to the increased surface area.

The 8-inch test motor was to be used as a test vehicle to determine the survivability of the insulated salt quench, the change in the motor operating environment, and the expulsion characteristics of the salt when the sheet explosive was detonated in the open air and then to apply the results to the 18-inch test motor and attempt a termination.

2.3.1 Insulation Test Vehicle. The survivability of unprotected quench material in the combustion environment of a rocket motor has proven to be poor. Erosion rates of 0.05 to 0.06 in./sec have been recorded. If sacrifical quench material were added so that sufficient material remained at the time of termination, the overall design would suffer a severe weight penalty and would eliminate propellant. Therefore, an insulator was incorporated over both the nozzle and head-end quench charges. The insulation material was evaluated and selected based on results of tests in a 5-inch-diameter uncured end-burning test motor. The test configuration is defined on Thiokol Drawing LO-4546 (Figure 5).



1. ASSY NO (ASSY —) AND SERIAL NO (S/N —) TO BE MARKED PER TCC SPEC PI0001-10
2. APPLY ITEM NO 4 TO "O" RING AND THDS PRIOR TO ASSY.
3. BAG IGNITER TO CONTAIN 10 GMS OF 2A BORON PELLETS ($BKNO_3$) AND (1) DUPONT S67 SQUIB.

QTY REQD PER DASH NO -01	ITEM NO	CODE IDENT	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL	SPECIFICATION
1	5		3	BAG IGNITER		
AR	4		MIL G-4343	LUBRICANT		
1	3		AN6227B-56	"O" RING		
1	2		LO-4544	NOZZLE ASSEMBLY		
1	1		LO-4545	CASE, LOADED		

LIST OF MATERIAL OR PARTS LIST

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCES XX = ± .010 XXX = ± .010
ANGULAR ± 30' FRACTIONS ± 1/16
BREAK SHARP EDGES .003-.015
ALL SMALL FILLETS .020-.040 R
THREADS PER FED H IDDK H-28 AND SUPPLEMENTS
DIMENSIONING PER MIL-STD-8
WELD SYMBOLS PER JAN-STD-19
SURFACE ROUGHNESS SYMBOLS PER MIL-STD-10
ALL FINISHED SURFACES 125

DRAWN / CHECKED / ENGR / ENGR / ENGR / USER / STRESS / SAFETY / APPD

DESIGN ACTIVITY APPROVAL

Thiokol CHEMICAL CORPORATION
ELKTON DIVISION ELKTON, MARYLAND

MOTOR ASSY, INSULATION TEST, UNCURED ENDBURNER, TP-H-3062

CODE IDENT NO 07299 | SIZE D | LO-4546

SCALE | WEIGHT | CALC ACTUAL | SHEET

FIGURE 5. 5-INCH-DIAMETER END-BURNING TEST MOTOR

2.3.2 <u>8-Inch-Diameter Test Motor - TE-T-670</u>. The purpose of the 8-inch-diameter test motor (Figure 6) was to evaluate the performance and survivability of quench assembly configurations. The design of the quench assemblies was based on configuration constraints using an existing test motor rather than meeting a particular DCR or QCR since motor quench was not a requirement. Testing in this program phase was limited to two nozzle quench assemblies and two 8-inch motors.

The nozzle quench assemblies tested conformed to Thiokol Part Numbers E27344-01 and E27344-02. Both configurations were made from a steel housing, insulated graphite throat insert, silica phenolic exit cone, internal insulation, explosive sheet, detonator, and quench charge. The insulation covering the quench charges was omitted.

The DCR and QCR were to be the same on both test motors. The DCR for the nozzle quench assembly was 37.17 and the QCR was 0.0203. The DCR for the head-end injector assembly was 7.33 and the QCR was 0.0092. Thus, the total QCR was 0.0295, which is more salt than would be needed if the motor were to be quenched. However, the larger amount of salt was used since it represented the maximum amount that could be placed in the motor and more closely represented that which would be tested in the 18-inch motor. The higher DCR (less sheet explosive) was used since the quantity was a result of the area available for the sheet explosive If after the first test it was found to be insufficient, the DCR would be lowered by using a greater thickness of sheet explosive.

The test motor was designed to have a progressive-regressive pressure-time trace and to operate from 500 to 600 psia. Burn time was to be approximately 7.5 seconds. The propellant loaded, 18.4 pounds, was TP-H-3062, which is a carboxy-terminated polybutadiene (CTPB) high energy mix cure system having 16% aluminum. The propellant grain configuration was a circular center perforate with one end-burning design.

2.3.3 <u>18-Inch-Diameter Test Motor - TE-T-672</u>. The purpose of the 18-inch-diameter test motor (Figure 7) was to demonstrate combustion termination in a half-scale configuration of a TE-M-364 Delta type space motor. In general, all physical aspects were scaled down by a factor of two from the Delta size motor to the 18-inch test motor. However, the motor operating pressure was maintained at approximately 600 psia. The motor assembly is defined on Thiokol Drawing E27380-01. The motor is composed of four major subassemblies: the loaded case, igniters, nozzle quench assembly and head-end quench assembly (see Figure 8).

The motor case was manufactured from two standard steel 18-inch pressure caps welded together with attachment rings welded in for the end closures. A thrust skirt was welded to the forward cap and handling lugs to the aft cap. The case was insulated with an asbestos-filled polyisoprene rubber, and stress relief flaps were employed at the forward and aft ends.

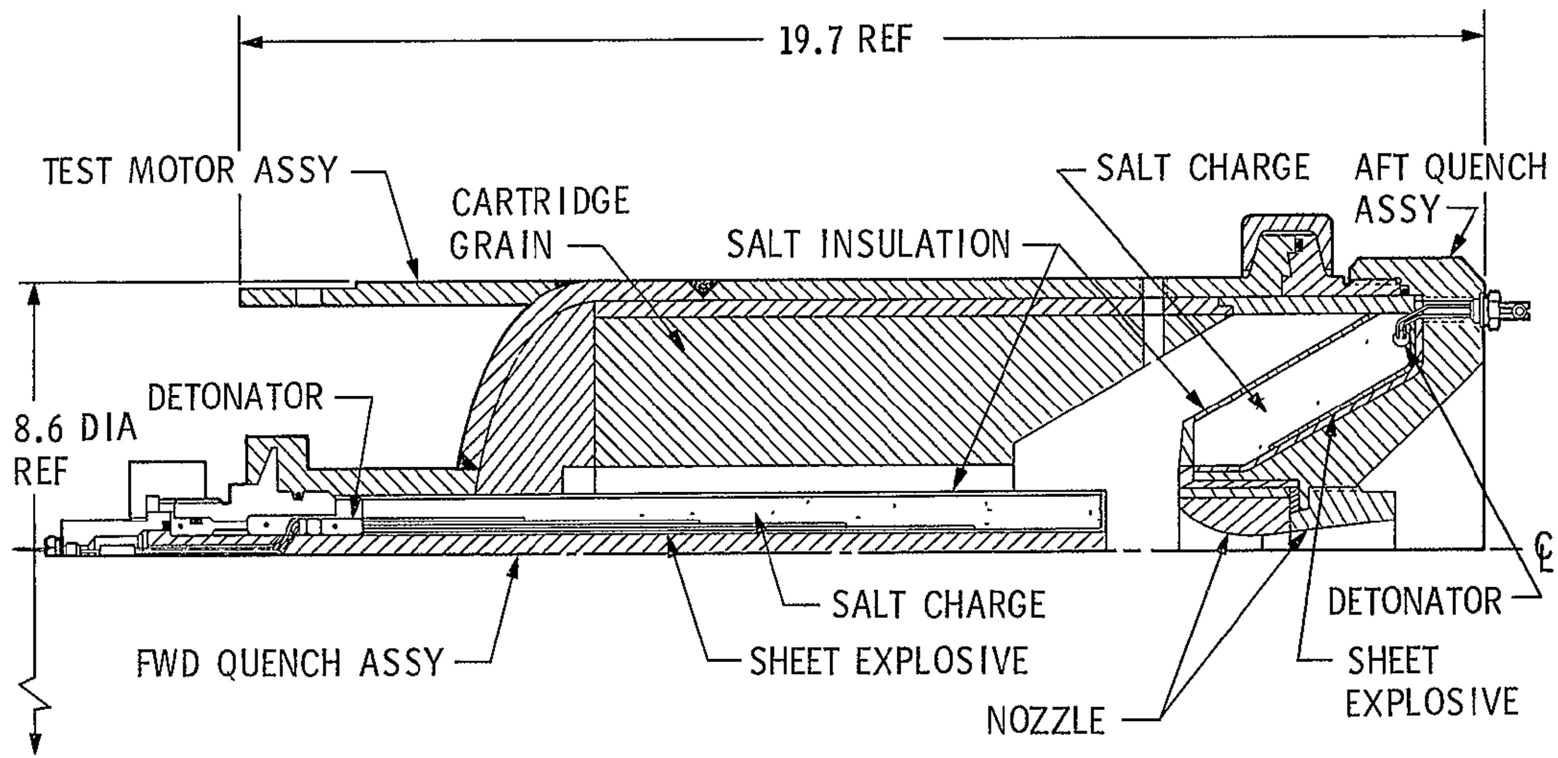


FIGURE 6. 8-INCH-DIAMETER TEST MOTOR

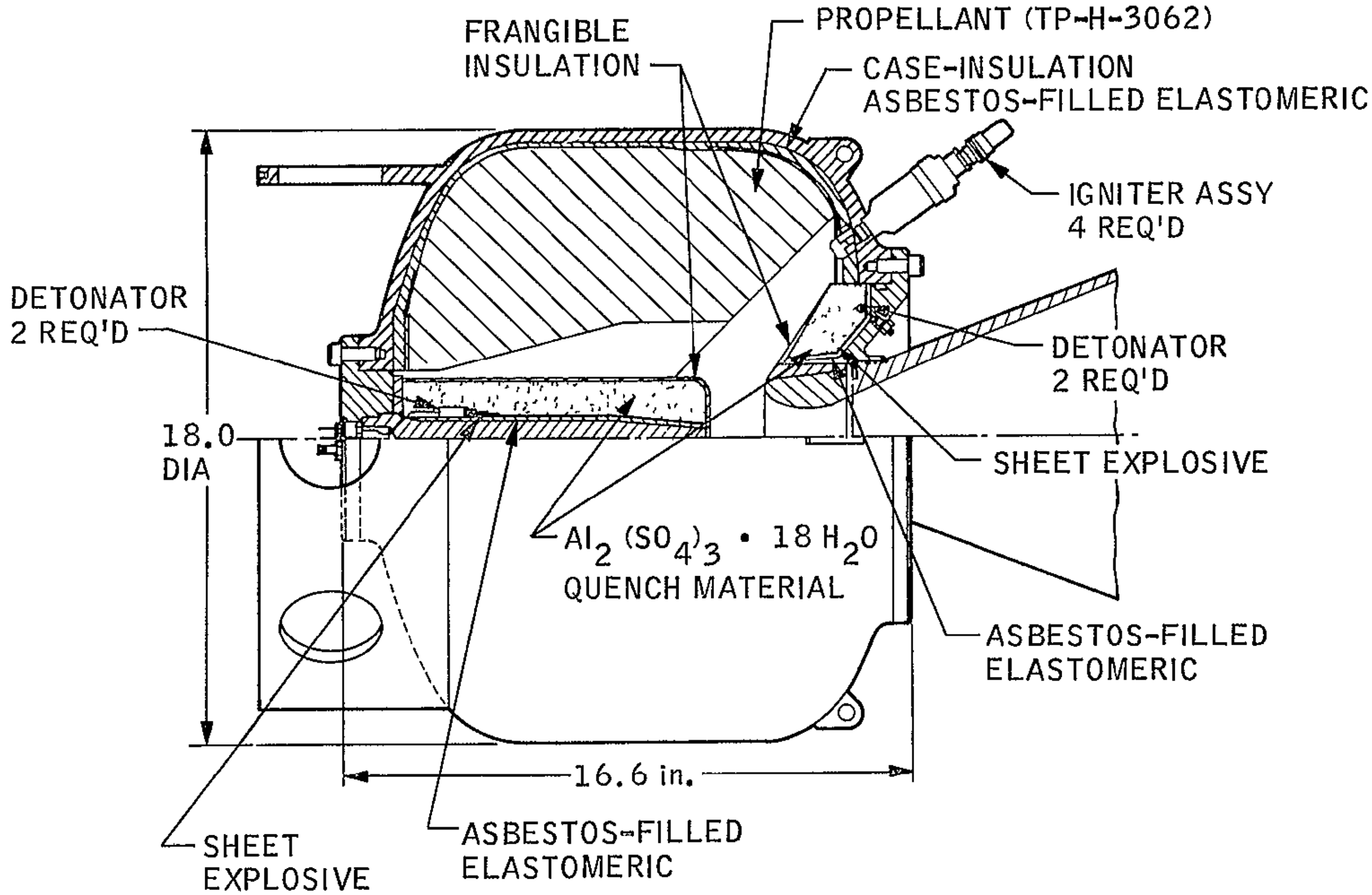


FIGURE 7. 18-INCH-DIAMETER TEST MOTOR

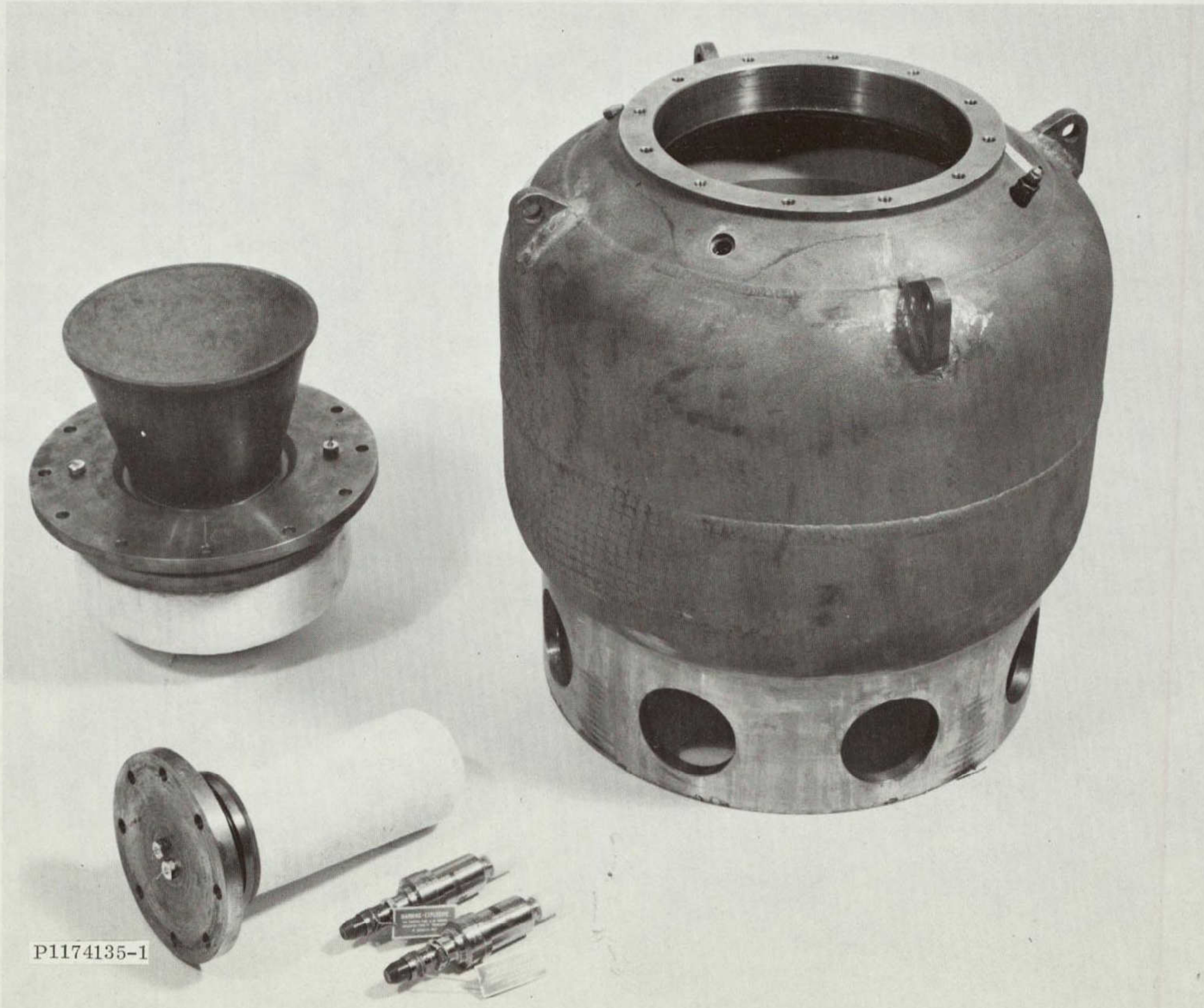


FIGURE 8. 18-INCH-DIAMETER TEST MOTOR COMPONENTS

The propellant grain was cast with TP-H-3062 propellant. The grain cavity was formed with a core and then modified by machining to remove the grain star points. The aft end of the grain was machined to an angle of 45 degrees to the grain centerline so that at the time of termination all propellant burning surfaces would be exposed to the quench material at an angle no greater than 45 degrees. Loaded propellant weight after machining was 126.5 pounds.

The motor ignition system is composed of two Gemini type igniters which are defined on Thiokol Drawing E15459. The igniters are mounted in the motor case aft end.

The nozzle quench assembly is composed of a steel closure, internal asbestos-filled polyisoprene rubber insulation, a fully insulated G-90 graphite throat insert with a rubber shock attenuator sleeve, and a plastic exit cone. The quench assembly is composed of two DuPont E94 detonators, 0.025-inch-thick sheet explosive, quench material, and alumina ceramic felt insulation. The quench charge was sized on the basis of available volume, which yielded a QCR of 0.014 at motor ignition. The sheet explosive was perforated in a manner similar to that used in the second 8-inch nozzle test, resulting in a DCR of 73.6.

The head-end quench assembly has a steel closure and mandrel, asbestos-filled polyisoprene rubber insulation over the mandrel, two DuPont E94 detonators, two two-pin pressure terminals, 0.025-inch-thick sheet explosive, quench material, and alumina ceramic felt insulation. The QCR of this assembly was 0.0089 and the DCR was 79.8.

The DCR's of approximately 70 to 80 were selected on the basis of the 8-inch nozzle test results where a lower DCR caused damage to the nozzle and components (see Section 2.5). From the two successfully quenched motors in the VBA tests, a QCR of 0.02 is required for termination. It should be noted that the total QCR of the two charges in the 18-inch test motor is 0.023, which should be sufficient to quench the motor.

2.4 Test Results of Insulation Test Motors

Two 5-inch uncured end burners were tested to evaluate various candidate insulation materials. The materials evaluated in the first test were cork (Armstrong 2755 cork), molded asbestos phenolic (Raybestos Manhatten RPD-150), alumina ceramic felt (Refactory Products Co. WRP-X-AQ felt), and paper phenolic (Thiokol Grade 550). Post-test evaluation showed a considerable throat buildup with the throat diameter reducing from 0.3064 to 2.350 inch. The pressure-time trace, which was supposed to be relatively neutral, was progressive. Since the material deposited in the throat was aluminized material, the felt insulation was suspected as the source as its chemical analysis shows 34.2% Al_2O_3.

The second test conducted duplicated the first except that the felt insulation samples were replaced with hydrated salt, $Al_2(SO_4) \cdot 18\,H_2O$. A progressive pressure-time trace was again noted and the throat diameter reduced from 0.307 to 0.220 inch. Results of this test eliminated the felt insulation as the source, and throat buildup is attributed to the aluminum in the propellant. Erosion results of the tested samples are listed in Table XII.

The condition of the cork samples after testing was comparable to their pretest condition after the char was removed. The samples had good flexibility and toughness. The material was rejected from further consideration, however, because of poor frangibility. The asbestos phenolic (RPD 150) was rejected for the same reason. Frangibility of the material is considered as important as insulation qualities.

The WRP-X-AQ felt is a good insulator and is very frangible; however, after exposure to the high temperature environment inside the rocket motor, an aluminum slag forms on the exposed surface. This could prevent termination by blockage or reignition by hot particles.

The paper phenolic (Grade 550) performed satisfactorily and a very frangible char layer remained. The frangibility of the virgin material was subsequently evaluated during VBA testing. The frangibility of the virgin material was determined to be unacceptable for this application and was therefore rejected.

Using the basic quench material as an insulator by letting the excess ablate away during motor burn was rejected for two reasons. First, the eroding material entering the combustion area would tend to reduce the combustion efficiency, and second, the amount of extra material thickness would be excessive; for example, an additional thickness of approximately 1/2 inch would be needed in a 44-second burn time motor.

Based on the results of the tests, both the paper phenolic and WRP-X-AQ felt are acceptable insulators. During fabrication, the felt material proved to be less costly to apply and was ultimately selected.

2.5 8-Inch-Diameter Motor Test Results

Before any motors were static tested, two nozzle quench assemblies were fabricated and tested. The tests were conducted in the open, and high-speed movie coverage was used to record dispersal pattern, particle velocity, and action time. The external insulation covering the quench charges was omitted for these two tests.

TABLE XII

SUMMARY OF INSULATION TESTS

Insulation	Test No.		Thickness, in.		Char Rate, in./sec	Post-Firing Condition
	1	2	Initial	Post Test*		
Cork, Armstrong 2755	X	X	0.25	0.17	0.0044	Charred and raised sections of surface. Some cracking. Remainder tough and resilient.
Asbestos Phenolic, RPD 150	X	X	0.25	0.26	-	Only slight charring. Some cracks on edges, parallel to surface. Retains strength.
Felt, WRP-X-AQ	X		0.25	0.26	-	Pitted and glazed surface. Brittle through sample.
Paper Phenolic, Grade 550	X	X	0.25	0.18	0.0040	Charred surface. Remainder tough. Poor frangibility.
Salt $Al_2(SO_4) \cdot H_2O$		X	0.28	0.15 to 0.06	0.007 to 0.013	Eroded surface. Hard, glazed surface after loose material removed. Erosion increases toward nozzle end.

*All char material removed

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The first nozzle tested conformed to Thiokol Part Number E27344-01. The following damage resulting from the test was observed:

1) The graphite throat insert was fractured both circumferentially and longitudinally.

2) The outer threaded support ring was ripped apart.

3) The insulation covering the internal portions of the nozzle housing was ripped beyond repair.

The observed damage resulted from too large an explosive loading. The DCR was 37.17. Corrective action was taken to reduce the explosive loading and to provide a shock attenuator between the throat insert and nozzle housing in the form of a rubber sleeve. The dispersal pattern, particle velocity, and action time were measured and recorded.

The second nozzle tested conformed to Thiokol Part Number E27344-02. Pretest and post-test photographs of the nozzle are presented in Figures 9 and 10. The throat insert in this nozzle design was shock isolated from the nozzle housing with a 0.125-inch-thick polyisoprene rubber sleeve. The explosive sheet was redesigned from a solid sheet to a multiperforate. The explosive weight load was reduced from 36.32 grams to 19.15 grams, which then yielded a DCR of 70.49.

No damage to the nozzle was observed after the test. The quench material dispersal pattern was uniform at an angle of 45 degrees. Particle velocity was calculated at 1730 ft/sec, and action time was 0.0017 second. Action time is defined as the time from when a photo flashbulb starts to light to when quench material starts to leave the nozzle.

The first TE-T-670 static test motor assembly conformed to Part Number E27418-02, as shown in Figure 11. A plot of motor chamber pressure versus time is presented in Figure 12. Figure 13 is a photograph of the various components before final assembly and Figure 14 is a post-test photograph of the injector and nozzle quench assemblies.

The ballistic performance of the motor was as predicted. At approximately 2.0 seconds after ignition, the motor chamber pressure was perturbated by material passing through the nozzle throat. The ejected material was probably the insulators covering the two quench assemblies. The detonator in the nozzle quench assembly had detonated sometime during motor operation, but the explosive sheet did not detonate. The detonator in the head-end injector assembly were still intact.

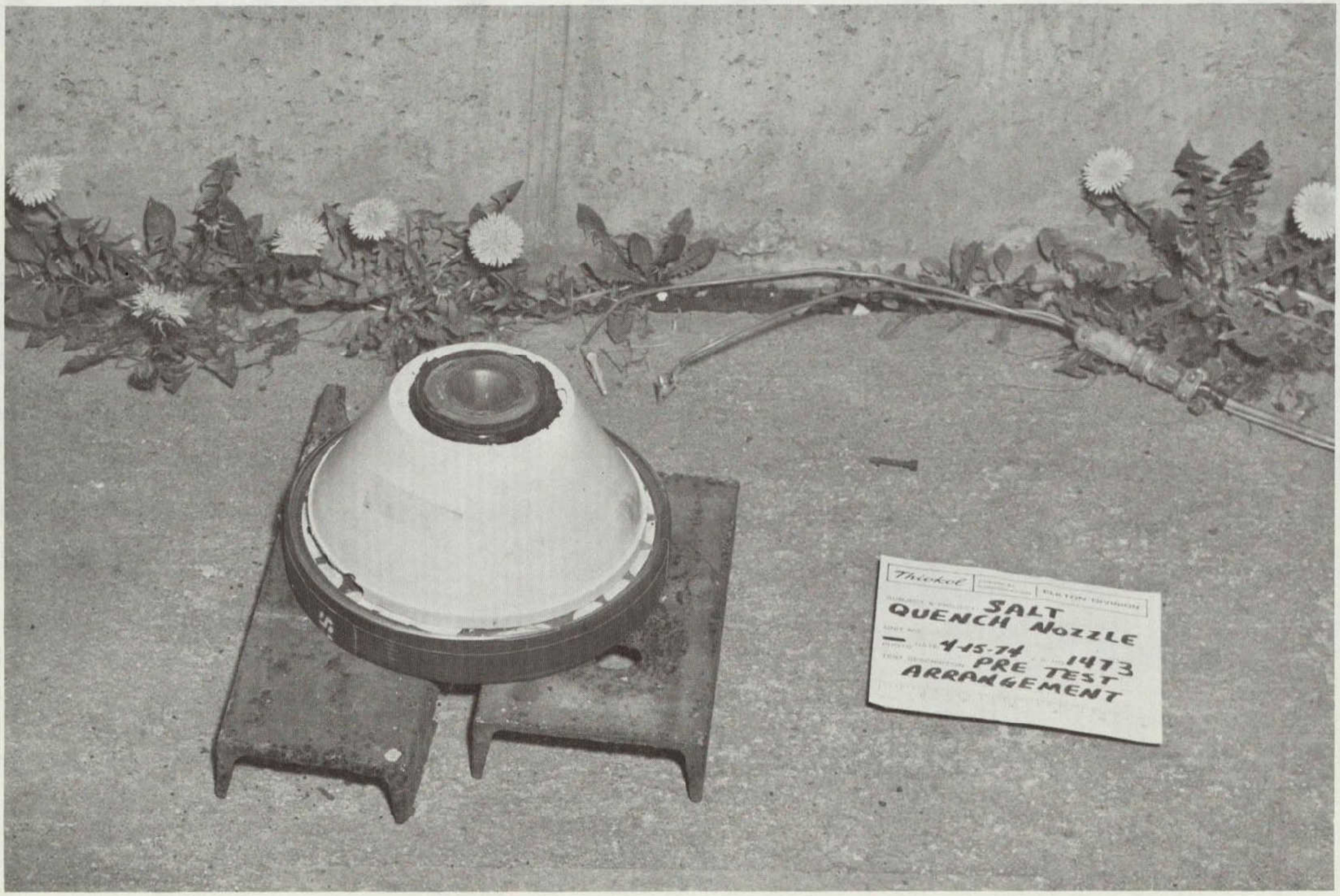

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FIGURE 9. SALT QUENCH NOZZLE, PRETEST ARRANGEMENT

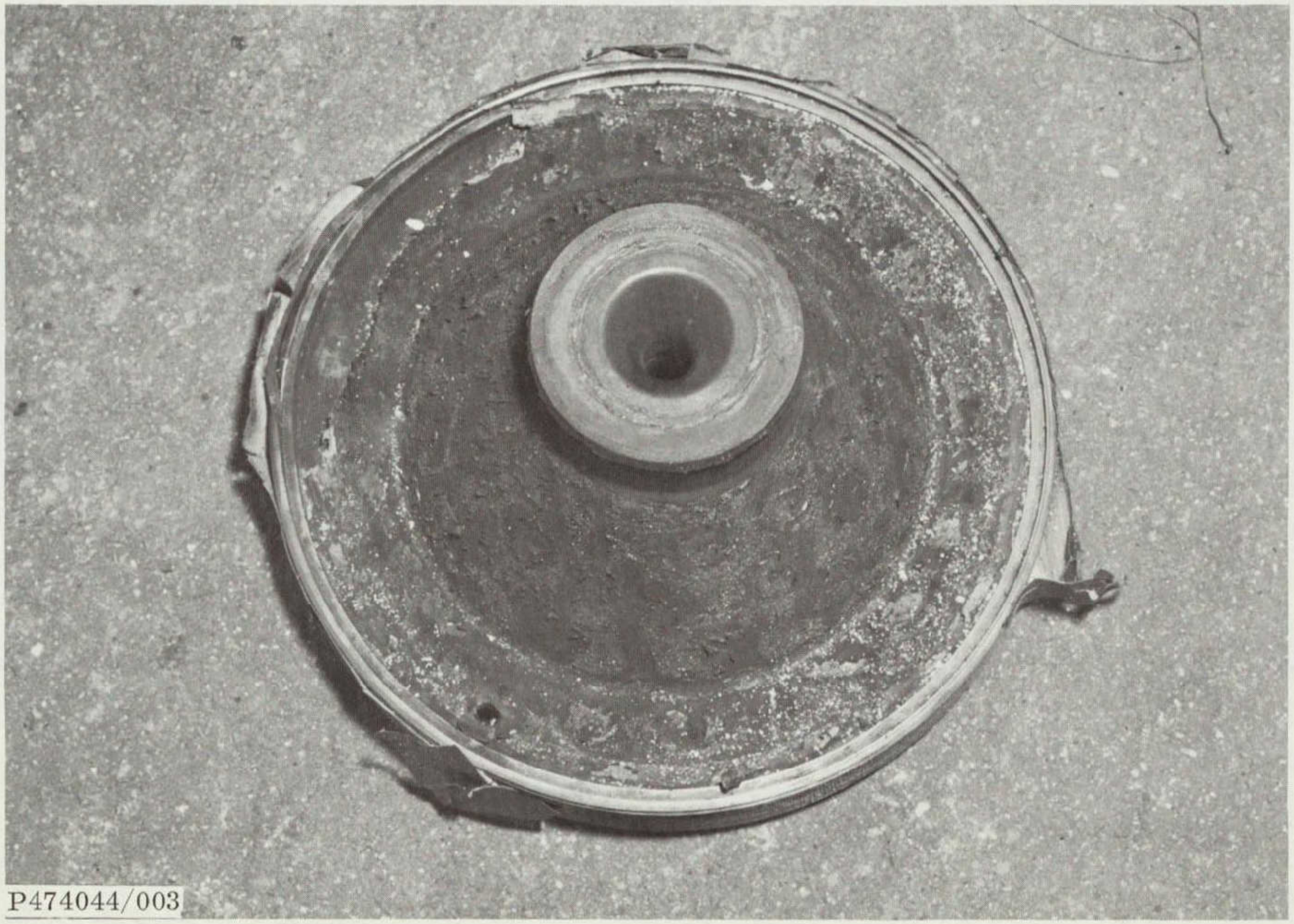

FIGURE 10. SALT QUENCH NOZZLE, POST-TEST ARRANGEMENT

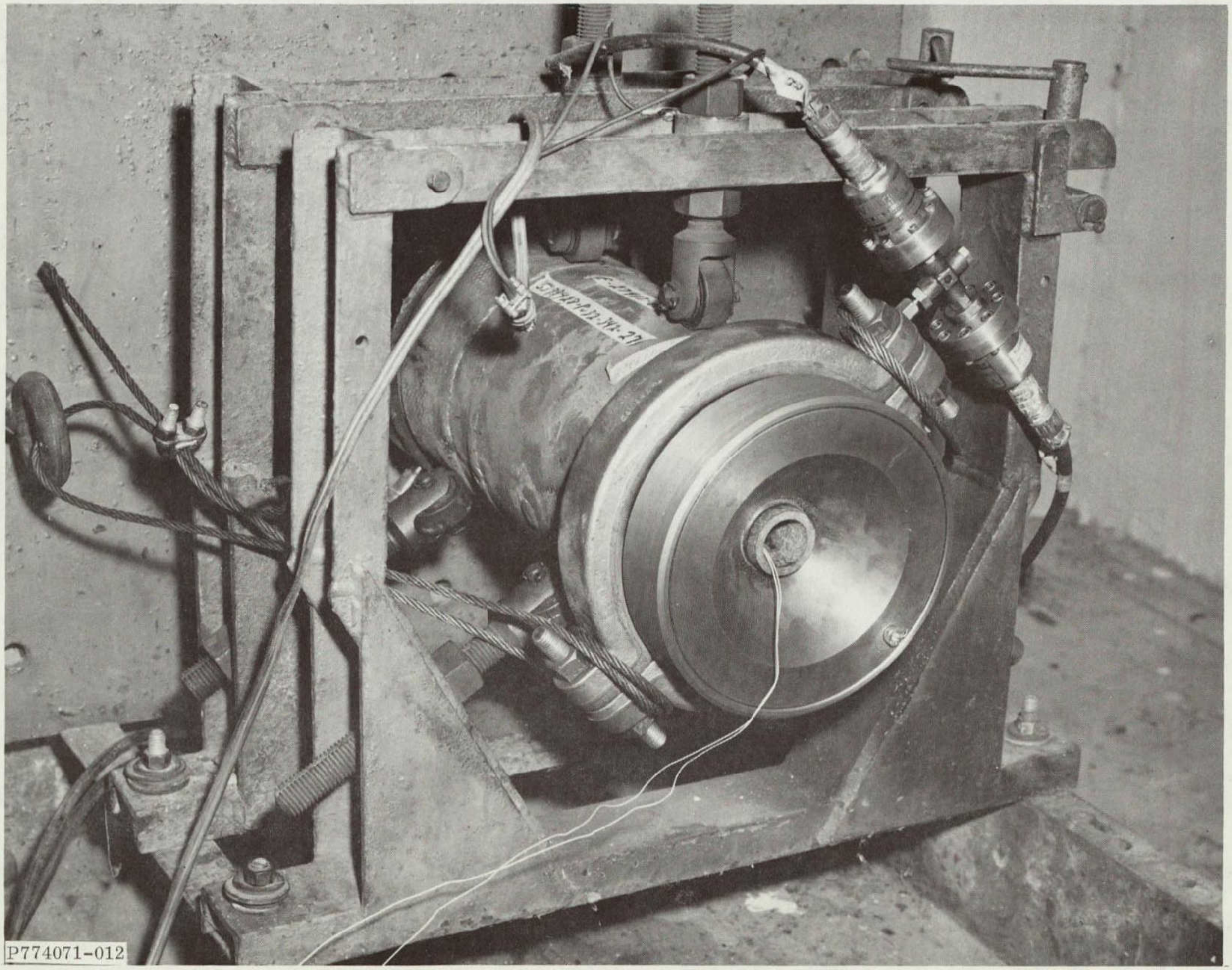

FIGURE 11. TE-T-670 MOTOR ASSEMBLY

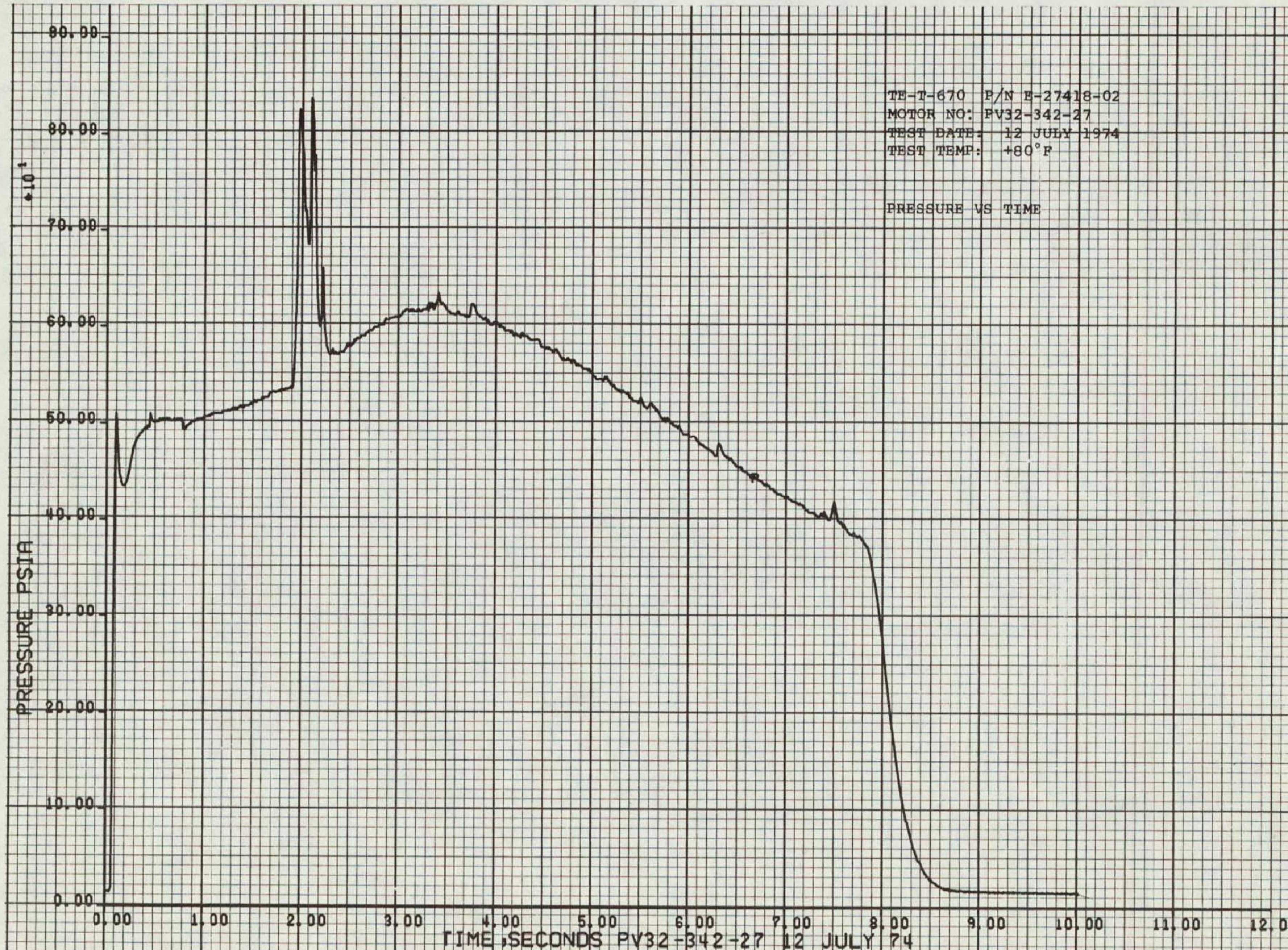

FIGURE 12. TE-T-670 MOTOR CHAMBER PRESSURE VERSUS TIME

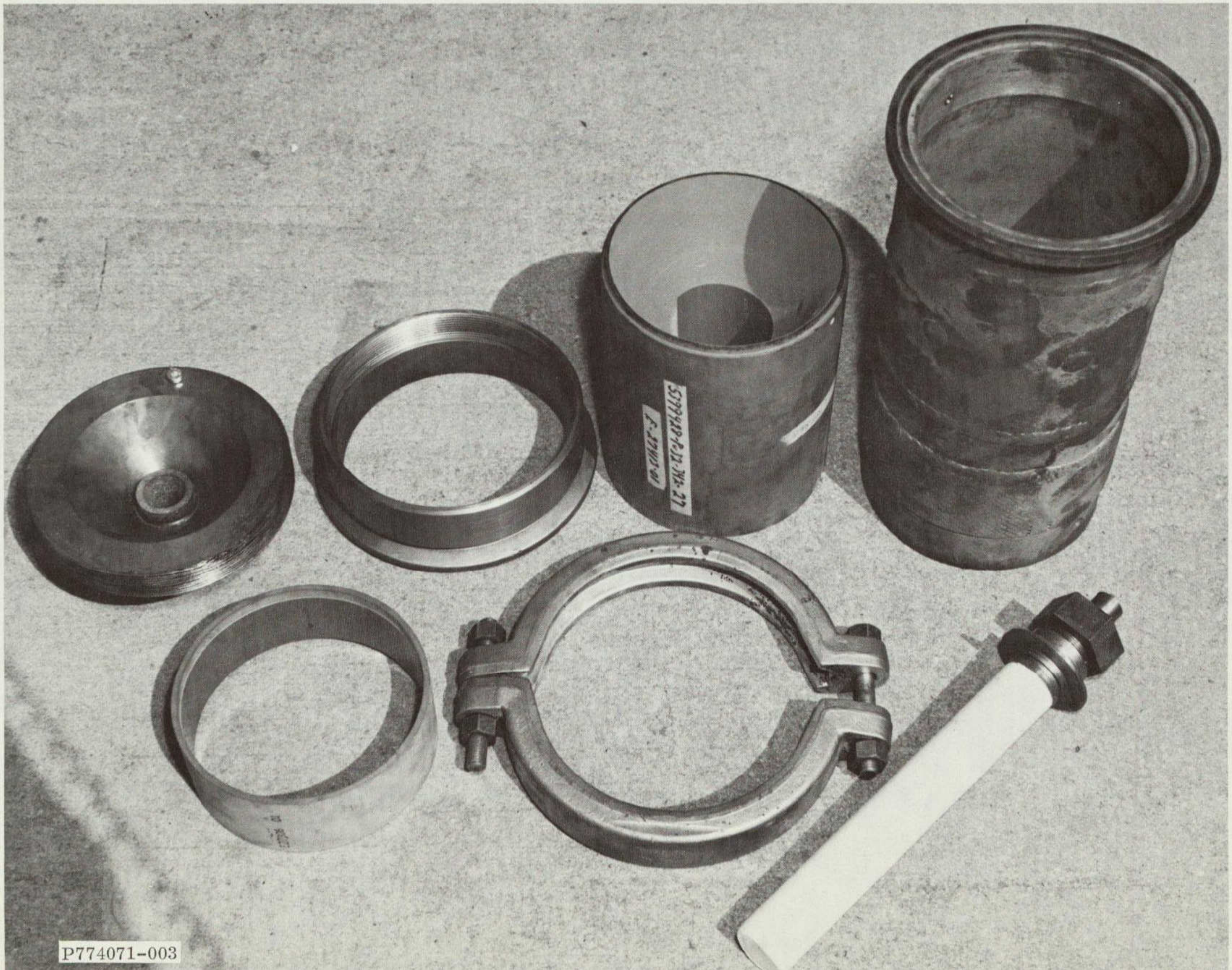

FIGURE 13. TE-T-670 COMPONENTS

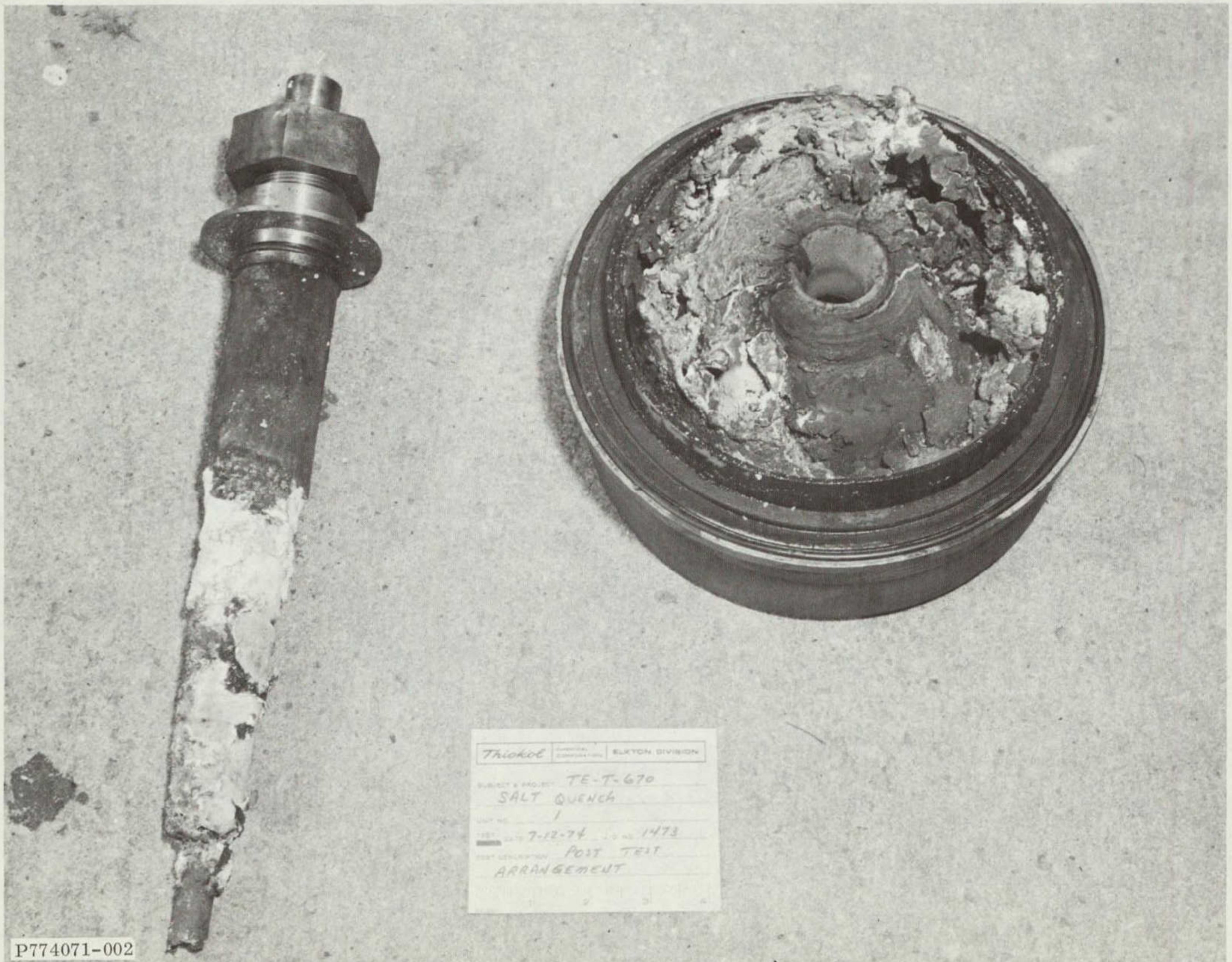

FIGURE 14. INJECTOR AND NOZZLE QUENCH ASSEMBLIES AFTER TEST

Figure 14 shows the injector assembly and nozzle quench assembly after being subjected to the motor operational environment. Both assemblies are missing major portions of external insulation and quench material. Erosion of the quench material off the head-end injector assembly was similar in performance to tests previously conducted in the insulation test motor. The remainder of the injector assembly was actuated to allow for safe handling and to reclaim the reusable components. The remaining explosive sheet under the quench material functioned properly when the detonators were fired.

All of the external insulation on the nozzle quench assembly was consumed along with approximately 55-60% of the quench material. The major area of quench material consumption was on that half of the quench ring that was on top in the test stand. This was a result of heat orientation due to the test attitude.

The results of this test raised questions as to the ability of the felt insulation to resist the erosion environment inside the combustion chamber. It was reasoned that the gas flow paths and gas velocities were sufficiently different from the insulation test motor environment that the measured erosion rate of the felt insulation was incorrect by an order of magnitude.

The second motor assembly static tested conformed to Part Number E27468-03. This motor differed from the first by using a different insulation to cover the quench charges. The replacement insulation selected, Thiokol TI-P-304, has been used in a number of rocket motor designs. The material is an asbestos phenolic mastic insulation which cures up into a tough brittle insulation with good erosion resistance.

Figure 15 is a plot of motor chamber pressure versus time and Figure 16 is a photograph of the various components after testing.

As seen in the pressure-time plot, the motor chamber pressure was perturbated twice during motor burn time. The interruption in the pressure occurred before the interruption in the first static test. Large portions of the quench assemblies were ejected at each pressure interruption. As shown in Figure 16, no quench material remained on the nozzle or injector assembly and the aluminum mandrel in the injector assembly was melted off to where the mandrel entered the bore section in the case head end.

2.6 18-Inch-Diameter Motor Test Results

The 18-inch test motor configuration is shown on drawing E27380, Revision B, and Figures 8 and 17. The motor consists of a loaded case, head-end quench assembly, nozzle-end quench assembly, and igniters.

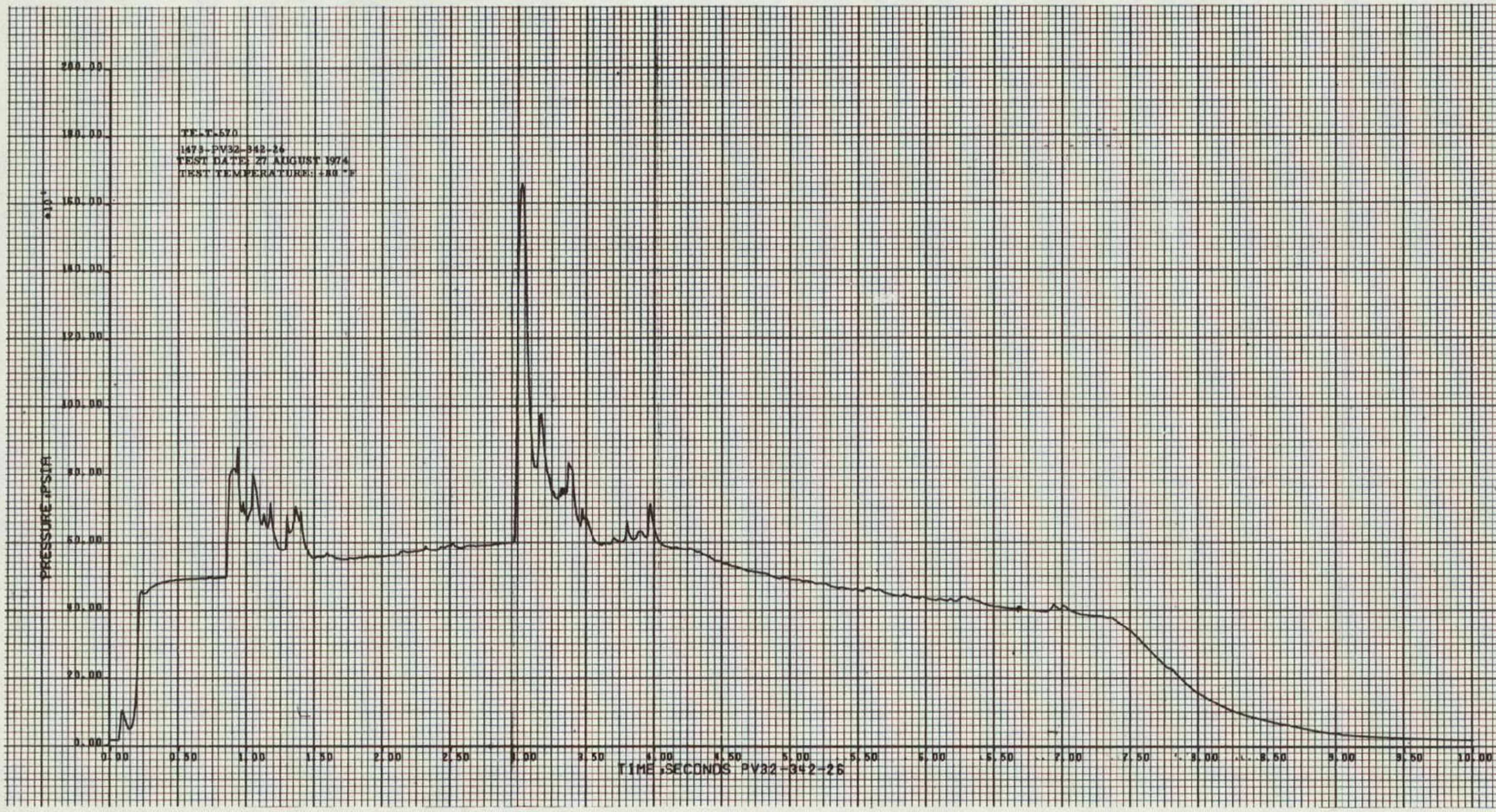

FIGURE 15. TE-T-670 MOTOR CHAMBER PRESSURE VERSUS TIME

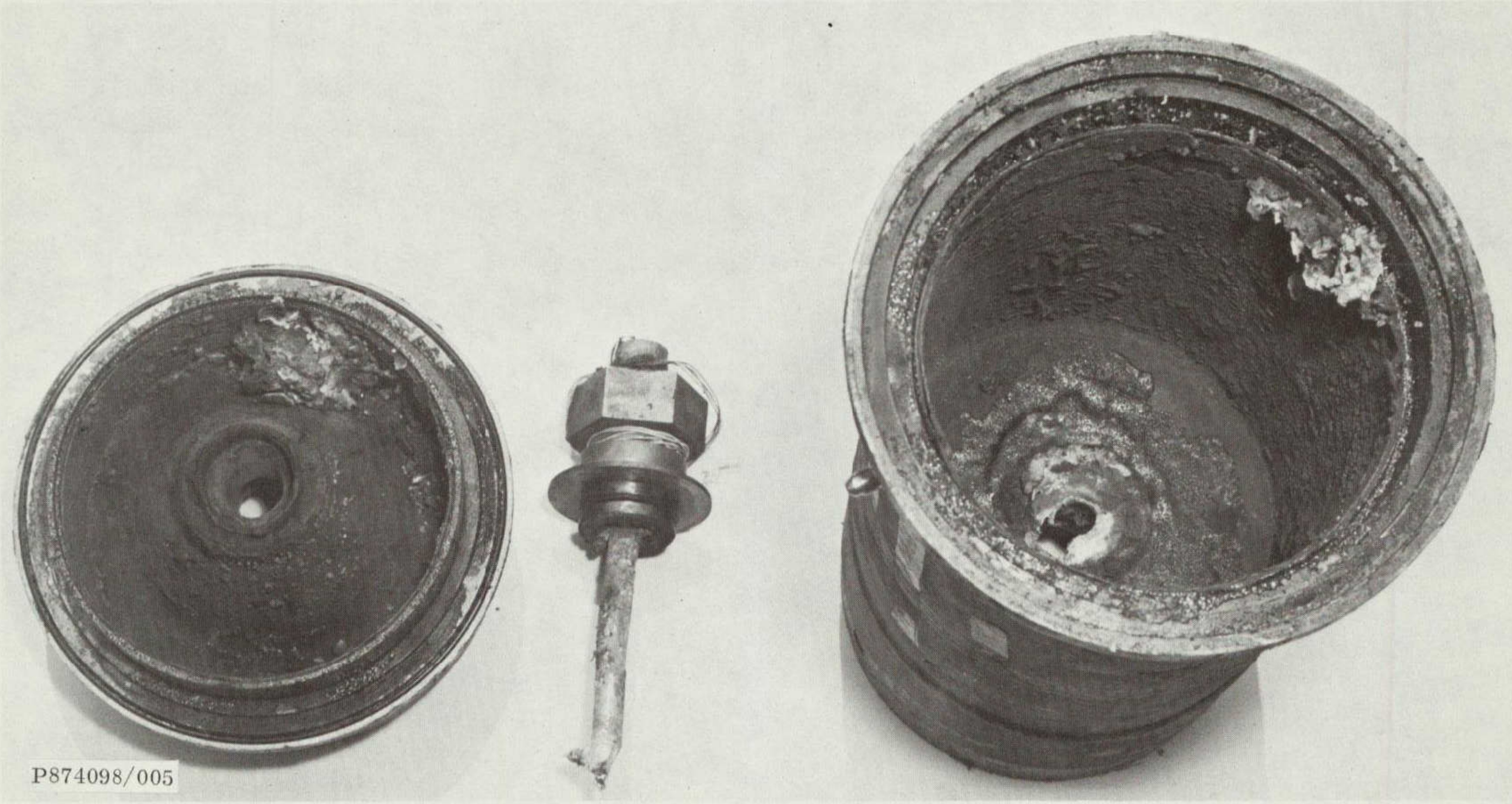

FIGURE 16. TE-T-670 AFTER TEST

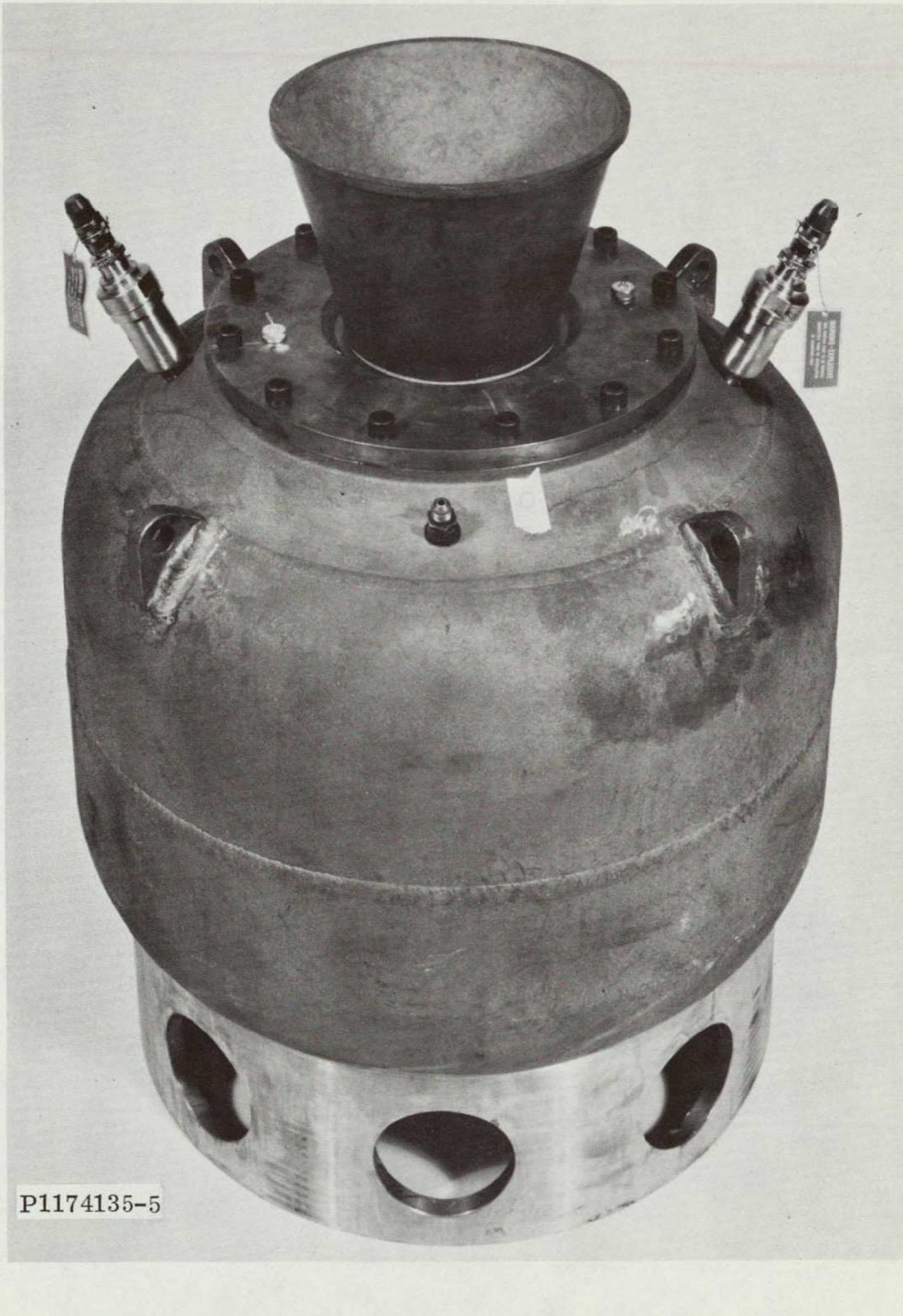

FIGURE 17. 18-INCH-DIAMETER TEST MOTOR ASSEMBLY

2.6.1 Head-End Quench Assembly. The head-end quench assembly is shown on drawing E27377 and Figure 18. The insulated mandrel was assembled to the head cap and a circular disc of insulation was bonded to the head cap. The explosive sheet (0.025-inch-thick) was attached to the mandrel using double-sided tape. At the detonator locations, the explosive sheet and double-sided tape were removed and the detonators were bonded directly to the insulation on the mandrel using TA-L-309 adhesive. A ramp of explosive sheet was fabricated to ensure initiation of the main charge and was in intimate contact with the end of the detonators. Total weight of the explosive sheet was 32.5 grams.

The salt charge was molded under pressure to achieve a final weight of 1566 grams after routing out of sufficient material to permit assembly over the detonators. A coating of adhesive (TA-L-309) was applied to the base of the salt quench charge and, in turn, was bonded to the circular insulator disc on the head cap. The internal cavity between the salt and mandrel was vented.

The insulation (WRP-X-AQ) was assembled to the salt without adhesive using the water in the uncured insulation to effect a bond between the salt and insulation by dissolving the surface salt and letting it flow onto the insulation. A disc of insulation was placed at the end of the salt and insulation was wrapped around the cylindrical section of the salt charge. One end was butted against the head cap, while the other end was contoured to overlap the insulation disc at the end of the salt charge. A second insulation disc was installed over the contoured ends of the cylindrical insulation to lock it in place and to provide maximum protection to the salt at the end where ablation might be a problem. The cylindrical insulation was overlapped so that at no place in the insulation would a straight gas path to the salt exist. The insulation was held against the salt by means of a stockinet material, which permitted the water to escape during cure yet held the insulation material tightly against the salt or itself during the initial cure (8 hours at 150°F + 4 hours at 150°F with the stockinet removed). Hardener for the insulation was applied after cure to prevent damage to the WRP-X-AQ insulation during handling and assembly.

2.6.2 Nozzle-End Quench Assembly. The nozzle quench assembly is shown on drawing E27376 and Figure 19. The procedure for attaching the detonators and explosive sheet was the same as outlined for the head-end quench assembly except that the explosive sheet was perforated to remove excess sheet explosive as was done for the latter 8-inch test nozzle assembly. The sheet explosive weighed 32.5 grams, and the salt quench weighed 2393 grams.

2.6.3 Loaded Case. The loaded case assembly and propellant grain configuration is shown on drawing E27897. The propellant was TP-H-3062 and weighed 126.5 lbs.

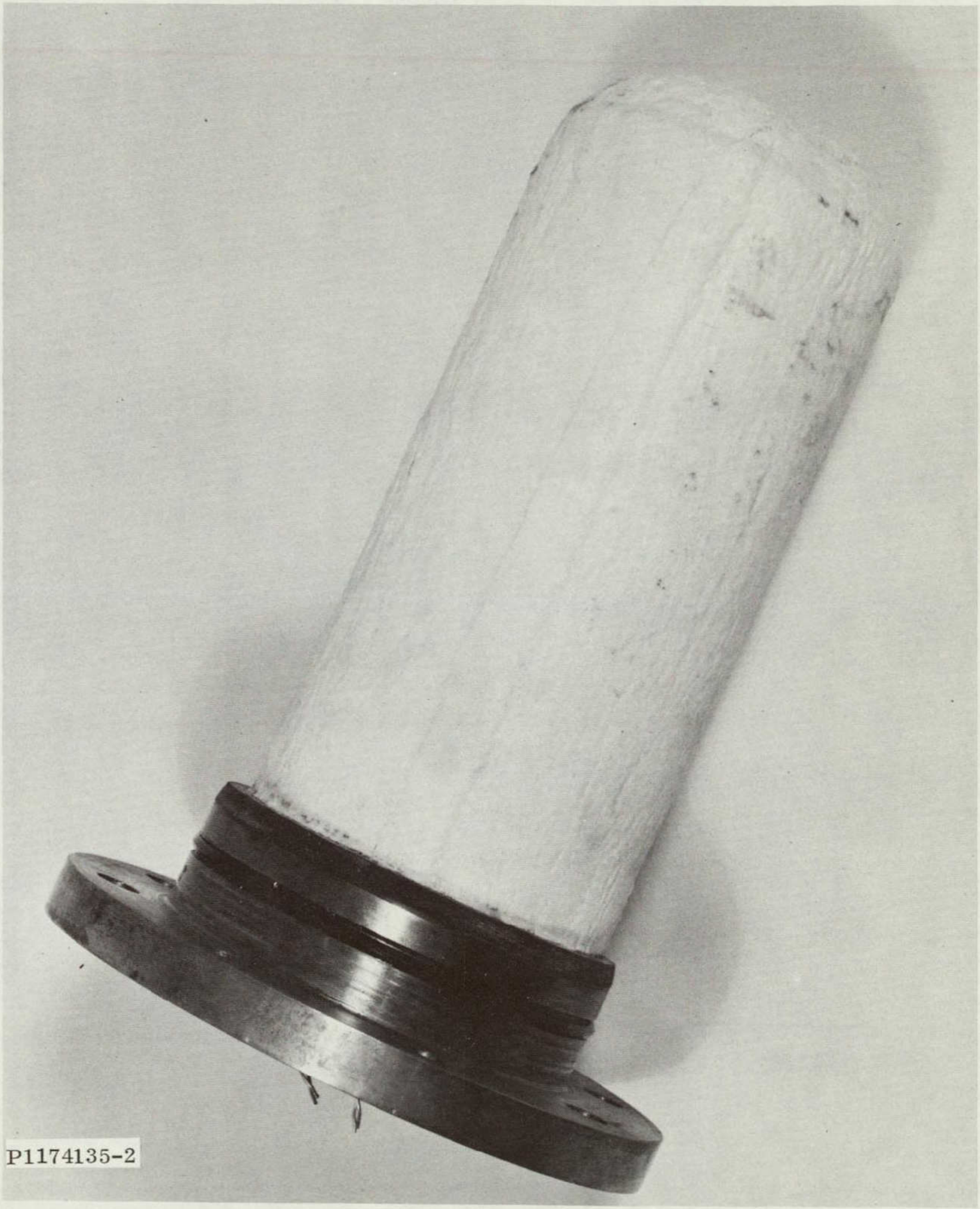

FIGURE 18. HEAD-END QUENCH ASSEMBLY

FIGURE 19. NOZZLE QUENCH ASSEMBLY

2.6.4 Igniters. Two igniters, E15457, were used to ensure full ignition of the propellant surface. The igniters are the same as used in the Gemini spacecraft retrograde motors.

2.6.5 Test Arrangement. The rocket motor components were assembled in accordance with drawing E27380. A vacuum pressure test was performed to ensure the integrity of all O-ring seals after assembly. The motor was assembled into the C-20 altitude facility in accordance with drawing E27381 and as shown in Figure 20.

A dry run was performed before static test to ensure that all data measurement systems were operating properly at altitude conditions. Four detonators of the same type as used in the quench charges were attached to the firing circuit and were detonated in the same sequence as to be used for the static test. The results of the dry run were reviewed, and all systems performed satisfactorily. Low level and high level pressure gauges were used to monitor motor chamber pressure during both motor operation and the quench sequence.

The motor was static tested in the C-20 facility with an initial cell pressure of 0.31 psia. The motor was ignited in 0.21 second, and termination was initiated at 0.98 second from 0 time. The pressure-time traces for the motor chamber and for the test cell are shown in Figure 21. Due to the location of the cell pressure gauge port in the test cell wall, the gauge responded to pressure from exhaust plume impingement and thus the pressure trace is labeled "exhaust plume pressure." The estimated cell pressure, without plume interaction, is included on Figure 21 for reference. As can be seen from the motor chamber pressure trace, the motor did not terminate. It continued to burn full duration.

Figures 22 and 23, respectively, show post-test views of the motor assembly and of the nozzle assembly. It should be noted that the two large portions of salt shown on the nozzle assembly in Figure 23 were recovered inside the motor chamber and have been fitted back into place on the nozzle to show how they conform to the nozzle shape.

2.6.6 Post-Test Observations. Post-test inspection of the motor components revealed the following:

1) It was evident that one of the two large portions of salt which fit the nozzle quench assembly had remained attached to the nozzle during test and had become dislodged afterward during post-test handling and disassembly operations. The noticeably different condition of the nozzle surface in the area where the salt remained supports this conclusion (see Figure 24).

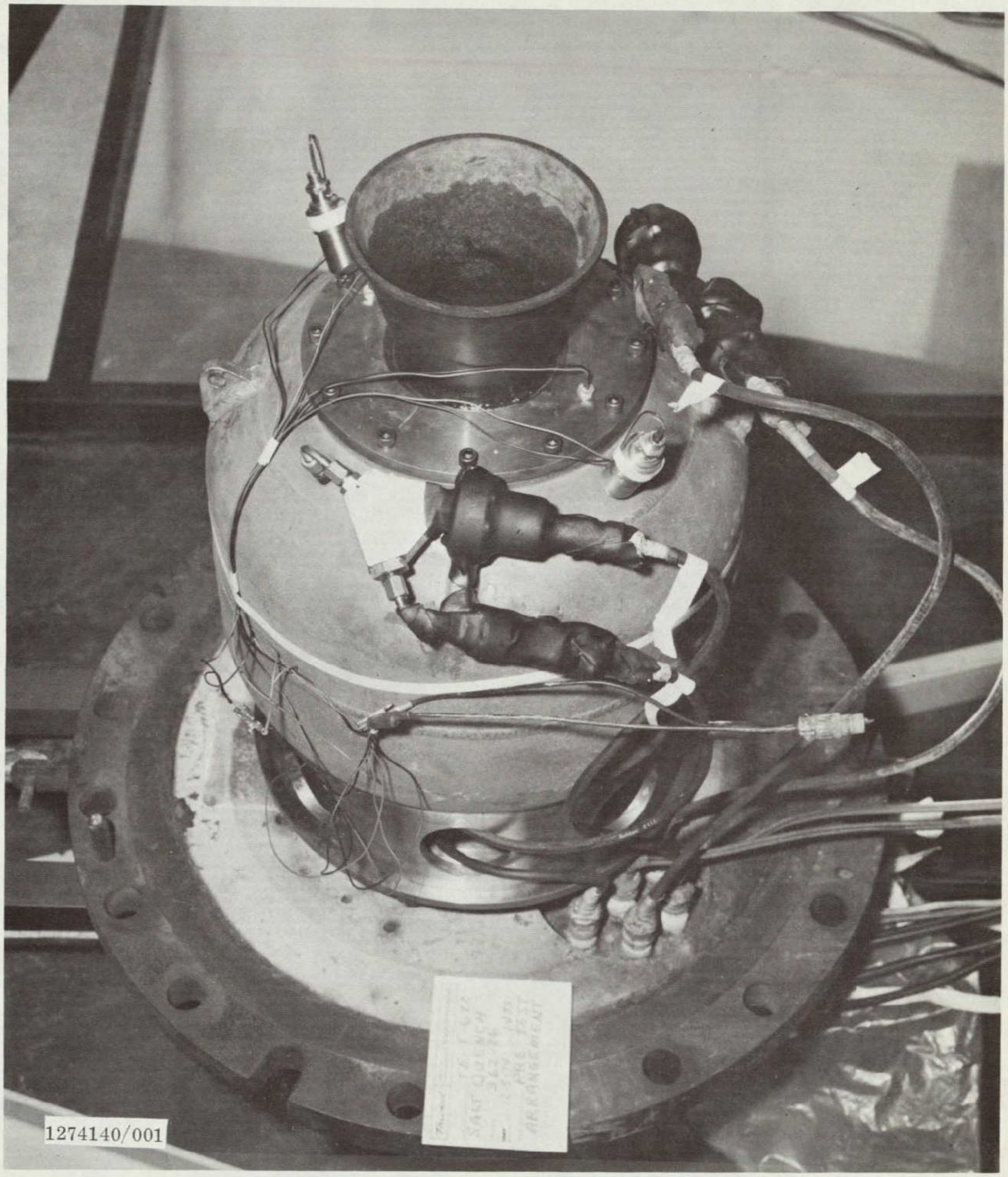

FIGURE 20. PRETEST ARRANGEMENT, TE-T-672

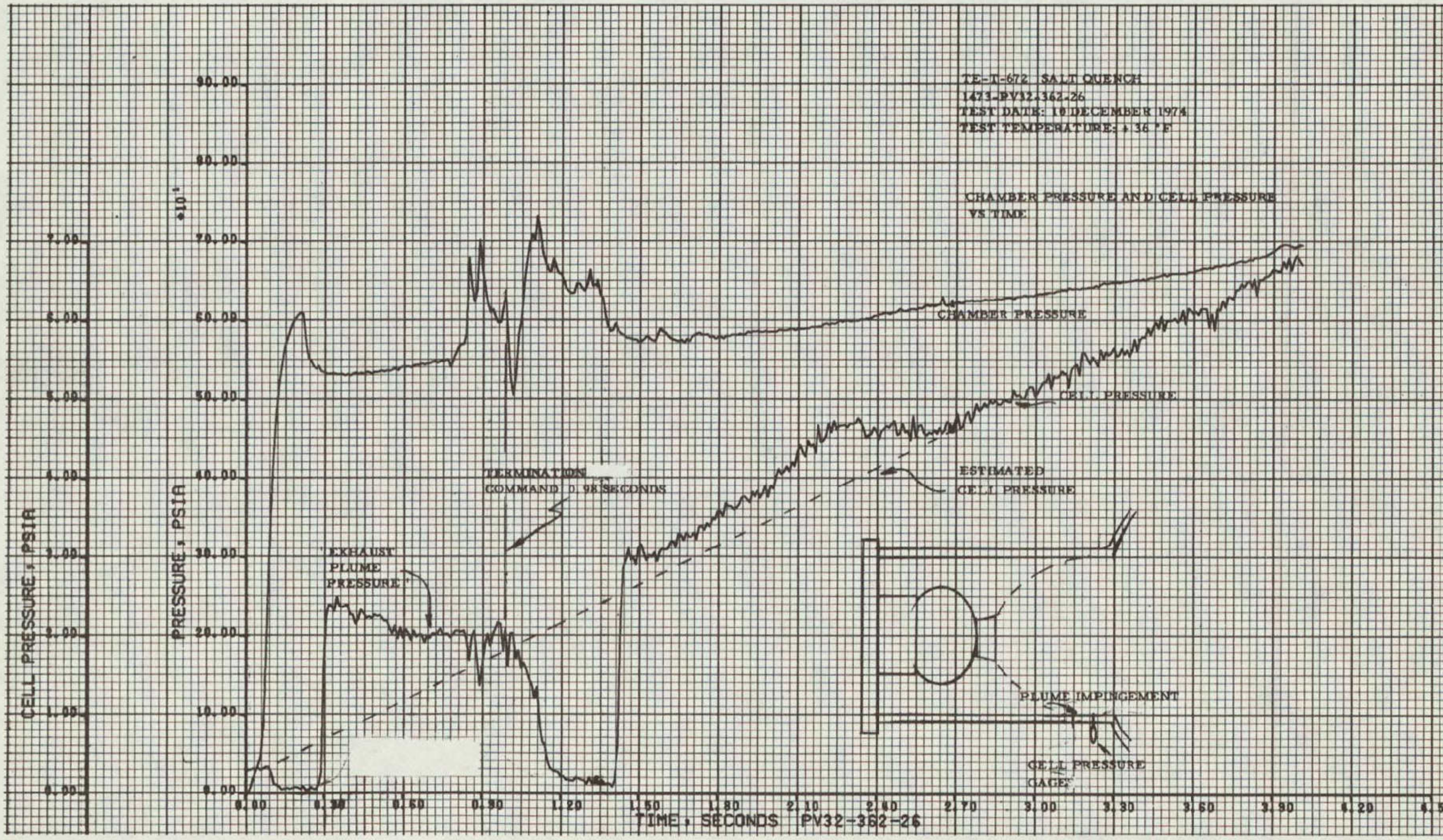

FIGURE 21. TE-T-672 MOTOR CHAMBER PRESSURE VERSUS TIME

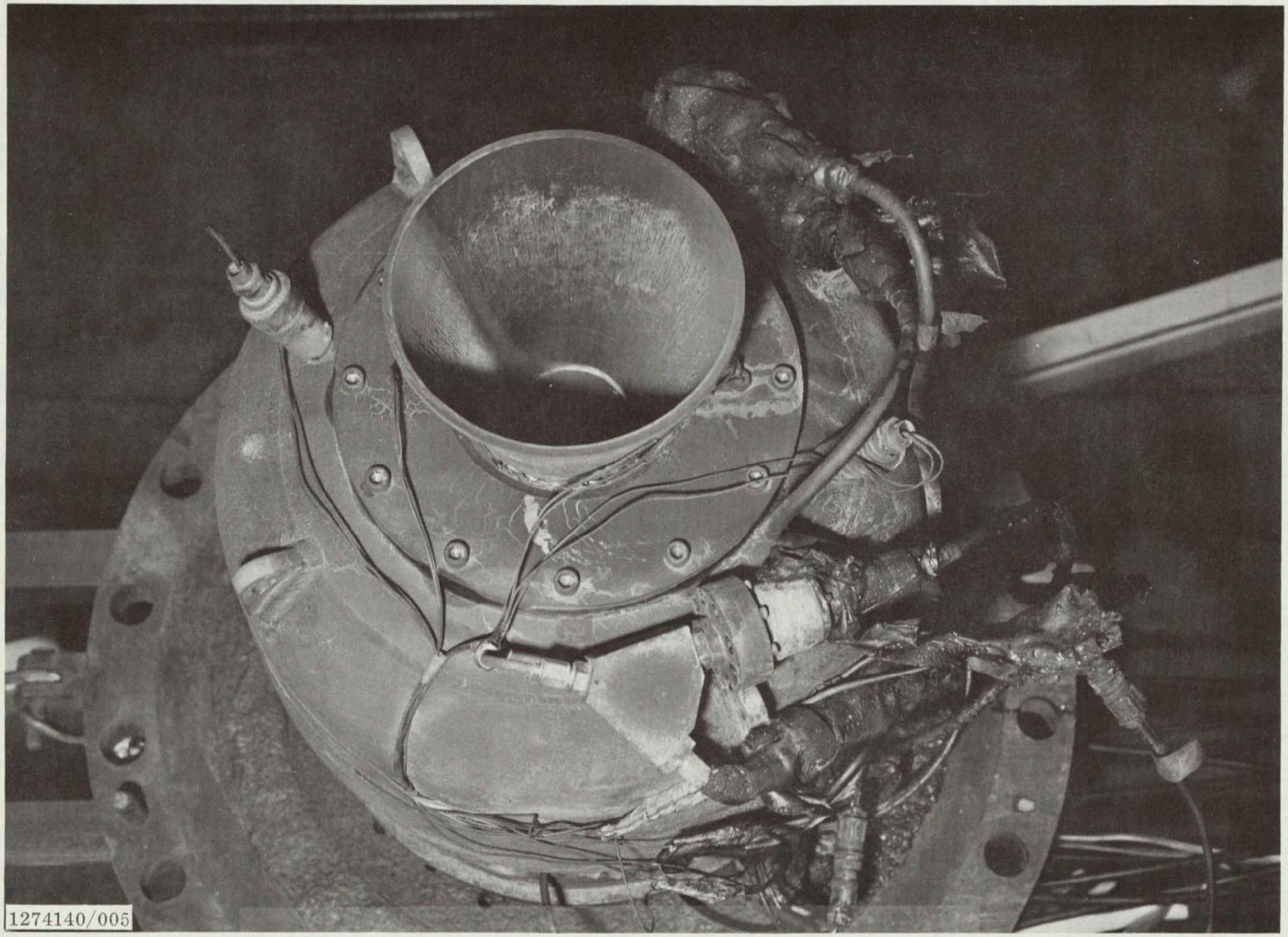

FIGURE 22. POST-TEST ARRANGEMENT, TE-T-672

FIGURE 23. NOZZLE QUENCH ASSEMBLY AFTER TEST

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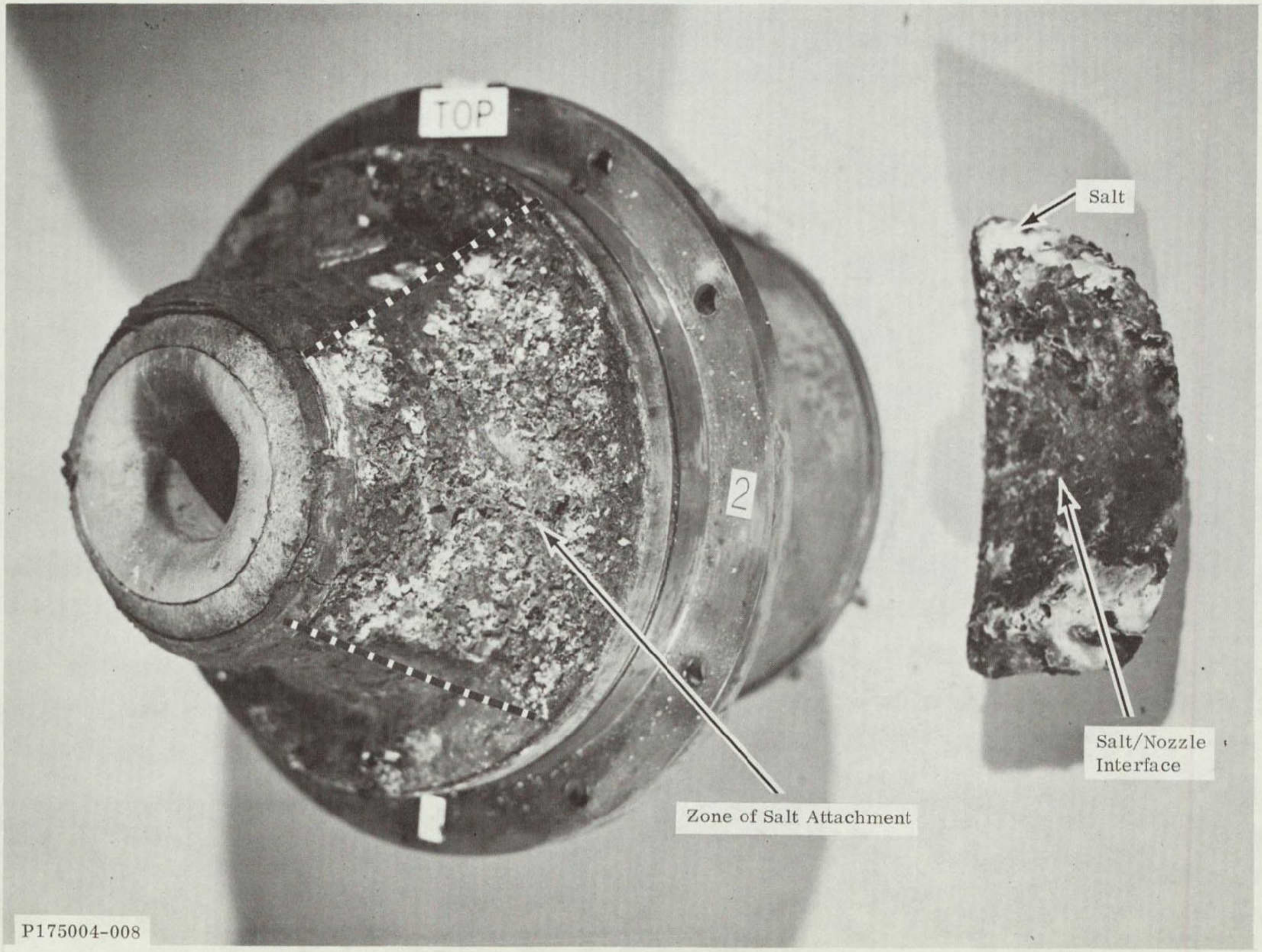

FIGURE 24. NOZZLE QUENCH ASSEMBLY AFTER TEST

2) No explosive sheet material was left on the nozzle assembly, and no remains of the detonators were found.

3) The insulation of the forward quench assembly mandrel was severely degraded, and the end of the mandrel (aluminum) was melted by exposure during motor operation.

4) Considerable salt slag was found inside the motor in addition to the two pieces which fit the nozzle assembly. There were no pieces that could be fitted or matched to the shape of the forward quench assembly mandrel.

5) The graphite throat insert was severely eroded at the entrance section and in the throat region.

2.6.7 Analysis of the Test Results. Based upon previous salt quench test experience, post-test examination of the components, and careful review of the analog records from the pretest dry run and the static firing test, the sequence of events that occurred are postulated to be as follows:

1) The motor ignited normally in the partial vacuum condition of the test cell and burned normally until approximately 0.78 second from zero time. The exhaust plume expanded sufficiently under the vacuum conditions to cause impingement and flow attachment forward of the cell pressure gauge port in the side of the chamber which housed the motor. This resulted in the cell pressure gauge reading becoming, in effect, a measure of the static pressure of the plume. Calculations indicate the static pressure of the plume for this condition to be approximately 0.16 psia. A decrease in motor chamber pressure after ignition resulted in movement of the plume attachment region aft toward the cell pressure gauge port. Thus, the cell pressure gauge during this time interval (0.30 to 1.15 second) measured the pressure in the flow attachment region. Between 1.15 and 1.40 second, the motor chamber pressure was sufficient to move the plume attachment region forward, and again the cell pressure gauge indicated the static pressure of the plume.

2) At 0.78 second from zero time, the insulation over the salt quench charges was degraded and eroded sufficiently to expose the salt charges so that they began to decompose. This kind of decomposition had been experienced in earlier tests of salt quench devices not protected by insulation. It is believed that products of decomposition of the insulation and the unprotected salt charge mixed with normal exhaust products and alternately "plated" out on, and eroded off of , the nozzle entrance and throat region, with the net result being a reduction of throat area and an increase in motor operating pressure. Further, the decomposition products of the insulator and the exposed salt charge added to the gas being evolved in the motor and thus contributed to the noted rise in motor chamber pressure which occurred starting at 0.78 second.

3) At 0.98 second after zero time, the detonators received their electrical actuation command signal. This is supported from review of the oscillograph records of command voltage and current in the detonator firing circuit for the pretest dry run in which four detonators, of the identical type as used in the static test, were fired using the same command circuit and equipment used in the static test. In comparing the recorded voltage and current traces from the pretest dry run with those of the static test, it is apparent that the detonator firing circuit was initiated in a normal manner and that there was no indicated malfunction in the command circuit or in the detonators up to and including opening of the bridgewires in the detonators. It is believed that the forward quench assembly explosive charge was detonated and that it did expel the salt charge remaining on the forward mandrel. The evidence for this belief derives from three observations:

a) The fact that no pieces of salt could be found to conform to the cylindrical shape of the forward quench material.

b) The precipitous drop in recorded motor chamber pressure to a level below normal operating pressure starting within about 3 milliseconds after the indication of detonator bridgewire opening.

c) Previous test experience with detonator operation times and onset of motor chamber pressure reduction caused by expulsion of salt quench charges into the motor chamber.

It is also believed that the nozzle assembly explosive charge did not detonate, as evidenced by the two large portions of salt found intact inside the motor chamber upon disassembly. From previous experiences in the VBA test series, it was noted that hot exhaust products will rapidly decompose the sheet explosive and that if this occurs in the region of the explosive sheet adjacent to the detonators, the propagation of detonation from the detonators to the sheet explosive does not occur reliably. The spatial relationship between detonator output and the explosive sheet in this test was the same as had been previously used successfully in 8-inch motor tests, however, and unless interrupted by the mechanism described above, should have been adequate.

4) Since the postulated action of the forward quench assembly and the failure of the nozzle quench assembly in combination were insufficient to cause termination, the remaining motor propellant continued to burn full duration with more of the "plating" and erosion discussed earlier for this test and as noted in earlier tests of the 8-inch test motor where irregular elevation of motor chamber pressure was observed intermittently (see Figures 12 and 15 in section 2.5). During this period, after the attempt to terminate, the remaining sheet explosive on the nozzle quench assembly burned away.

3.0 CONCLUSIONS

1) The VBA tests were not conclusive in determining the DCR and QCR required to quench TP-H-3062 propellant in a rocket motor. In the two cases where the propellant was quenched without reignition, the tests could not be repeated successfully. Minimum standoff distance was not established, and the effect of incidence angle was not determined. Use of the DCR values obtained from the VBA tests would cause structural damage to motor components and could not be used in the larger motor tests.

2) The insulation design selected to protect the quench charges, while having good frangibility, good adhesion to the salt charge, and good insulation characteristics, did not have acceptable erosion resistance in the rocket motor combustion environment.

3) Increasing the DCR from 37.17 to 70.49, which decreases the amount of explosive, in the 8-inch-diameter motor nozzle quench assembly still provided acceptable fragmentation and dispersal of the quench charge.

4) If the DCR and QCR are sized correctly, the condition of the terminated propellant burning surfaces will be relatively smooth. If the DCR is sized too low, then the terminated propellant burning surface could be damaged by the high velocity impingement of the quench material.

5) Failure of the nozzle quench insulation and the nozzle charge to remain intact during motor operation was probably caused by rapid decomposition and erosion of the quench charge reacting to motor environment.

6) The failure of the nozzle quench assembly to function as intended during the final 18-inch-diameter subscale motor test was probably caused by the failure of the detonators to set off the explosive sheet, which had become decomposed during motor operation.

4.0 RECOMMENDATIONS

The results to date indicate that a solid propellant rocket motor could be quenched using an explosive charge and a solid quenchant. The work accomplished has been of an exploratory nature, and additional investigative work is required to overcome the problems that prevented successful extinguishment of the 18-inch-diameter test motor. The major problem areas for the 18-inch test motor have been identified in this effort as the quench charge insulation and dispersant mechanisms. In addition to the definition of the problem areas, several accomplishments have been made such as the use of an elastomeric material at the throat insert to attenuate shocks to the insert and the perforation of the Detasheet to provide less destructive dispersant of the quench material. The problem areas requiring the most immediate attention are discussed below.

Based on the results of the program described herein, it is evident that additional investigation is required to demonstrate the feasibility of the quenching of solid propellant rocket motors with salt and to characterize the extinguishment mechanism sufficiently to permit its incorporation into flight rocket motor designs. This additional effort should first be directed toward perfection of a salt quench charge configuration and an explosive system which will deliver the quenchant to the propellant grain to effect extinguishment in a reliable, reproducible manner. A major consideration in designing the quench charge will be the thermal protection of the quenchant during the rocket motor operation.

It is suggested that these studies be conducted using components and test motors of a size sufficient to evaluate the conditions that will exist in flight motors. Test motors containing at least 100 pounds of propellant, such as the 18-inch motor used in this program, should be considered. Finally, it is recommended that additional propellant systems be investigated to determine the effects of propellant composition and burning characteristics on combustion termination. Studies conducted at the University of Utah[13] indicate the HTPB will extinguish more easily than the propellant formulation previously tested.

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APPENDIX A

SUMMARY OF VBA TEST DATA

APPENDIX A

SUMMARY OF VBA TEST DATA

Notes concerning entries in the Table A-1

QCR = Values expressed as pounds of salt per square inch of burning or exposed propellant surface

DCR = Values expressed as pounds of salt per pound of sheet explosive in quench assembly. Numbers in parentheses are calculated for the amount of sheet explosive originally placed in quench assembly. Actual DCR values must be calculated from the amount of sheet explosive initiated.

Sheet Explosive Shape		
	○	= flat disc, whole
	+	= flat cruciform or cross
	tab or ramp	= multilayered section, built up
	○	= flat disc with holes cut out to adjust weight
	button	= small disc bonded to edge of flat disc or cross to provide contact with det.

TABLE A-I

SUMMARY OF VBA TEST DATA

VBA No.	QCR, lbs/in.²	DCR, lb/lb	Detasheet Thickness, mil	Detasheet Shape	Detasheet Weight, g	Salt Charge Height, in.	Salt Charge Density, g/cc	Salt Charge Weight, g	Insulator	Standoff Distance, in.	Incidence Angle, degrees	Vacuum Level, mm	Detasheet Initiated	Pressure At Quench Signal	Pressure Reduced To	Burnout	Residues	Remarks
-01	0.111	(343)	8	⊃	0.41	2.00	1.69	139	Phenolic, 60 mil	6.0	0	44	Burned	590	-	Yes	Melted, not dispersed	Nozzle plugged, rupture disc blew
-02	0.056	(160)	8	⊃	0.43	1.00	1.68	69.1	Phenolic, 60 mil	6.0	0	34	Burned	680	480	Yes	Not dispersed	
-03	0.056	(25)	45	⊃	2.72	1.00	1.67	69.1	Phenolic, 60 mil	6.0	0	34	Burned	540	-	Yes	Melted, not dispersed	Rupture disc blew
-04	0.047	(390)	8	–	0.15	1.07	1.36	59.3	Phenolic, 60 mil	6.0	0	28	Burned	860	690	Yes	Melted, not dispersed	Witness plate first used
-05	0.012	(3)	45(x2)	–	1.90	0.26	1.39	14.6	Phenolic, 60 mil	6.0	0	33	Burned	550	470	Yes	Foamed, partial cylinder	
-06	0.023	(5)	45(x2)	⊃	5.48	0.52	1.39	29.4	Phenolic, 60 mil	5.9	0	33	Burned	590	510	Yes	Partial cylinder	
-07	0.014	(6)	45	○	2.76	0.50	loose	17.6	Phenolic, 60 mil	6.0	0	32	Burned	565	400	Yes	Foamed	
-08	0.022	(30)	45	+	0.93	0.50	1.39	28.2	Phenolic, 60 mil	6.0	0	26	Burned	635	490	Yes	Foamed, partial cylinder	
-09	0.012	(16)	45	–	0.93	0.26	1.40	14.6	Phenolic, 60 mil	6.0	0	25	Burned	860	690	Yes	Fragmented only	
-10	-	25	45	+	1.21	0.53	1.38	29.8	None	-	-	--	Yes	700	-	-	92% -30	700 psig dry N_2 used
-11	-	27	45	+	1.11	0.54	1.33	29.5	Phenolic, 60 mil	-	-	--	Yes	700	-	-	71% -30	700 psig dry N_2 used
-12	-	28	45	–	1.06	0.55	1.34	30.0	Phenolic, 15 mil	-	-	--	Yes	700	-	-	80% -30	700 psig dry N_2 used
-13	0.023	27.1	45	+	1.06	0.52	1.36	28.7	Phenolic, 15 mil	6.0	0	17	Yes	580	0	No		Tape filling voids around salt
-14	0.023	57	25	+	0.50	0.52	1.35	28.5	Phenolic, 15 mil	6.0	0	22	Yes	720	40	Yes		TA-L-309 fillet used to fill voids
-15	0.023	(165)	8	+	0.17	0.52	1.35	28.4	Phenolic, 15 mil	6.1	0	25	No	570	430	Yes		Tape filling voids
-16	0.012	13.6	45	–	1.06	0.26	1.36	14.4	Phenolic, 15 mil	5.9	0	28	Yes	710	0	Yes		Tape filling voids
-17	0.047	(61)	45	+	0.97	1.08	1.35	59.4	Phenolic, 15 mil	6.0	0	23	11%	610	250	Yes		Tape and TA-L-309 used
-18	0.012	26.8	25	+	0.55	0.26	1.36	14.6	Phenolic, 15 mil	6.0	0	27	Yes	670	0	Yes		Tape used
-19	0.035	(27)	45	+	1.60	0.76	1.40	43.1	Phenolic, 15 mil	6.0	0	28	No	920	-	Yes		Tape and TA-L-309 used
-20	0.023	(57)	8	–, tab	0.50	0.51	1.36	28.5	Phenolic, 15 mil	6.0	0	24	74%	685	280	Yes		TA-L-309 used
-21	0.035	(54)	25	+	0.79	0.75	1.40	43.0	Phenolic, 15 mil	6.1	0	31	No	670	375	Yes	Not dispersed	Tape and TA-L-309 used
-22	0.011	(76)	8	–	0.19	0.26	1.36	14.2	Phenolic, 15 mil	6.0	0	32	No	865	-	Yes	Some cake remains	TA-L-309 used, rupture disc at 7 seconds
-23	0.035	(13)	25/45	+/○	3.22	0.75	1.41	43.2	Phenolic, 15 mil	6.0	0	32	No	800	620	Yes	Some cake remains	Tape and TA-L-309 used
-24	0.012	(7)	45	⊙	2.15	0.25	1.41	14.4	Phenolic, 15 mil	6.0	0	24	No	700	-	Yes	Foamed plug of salt	TA-L-309 used hereafter
-25	0.034	(27)	45	+, -button	1.60	0.76	1.39	43.0	Phenolic, 15 mil	6.0	0	28	17%	680	660	Yes	Fragmented only	
-26	0.022	13.1	25	○, ramp	2.08	0.50	1.39	27.3	Phenolic, 15 mil	6.0	0	28	Yes	0	-	-	Salt dispersed	Pyrogen did not fire
-27	0.035	13.3	25/45	+/○, button	3.24	0.76	1.39	43.0	Phenolic, 15 mil	5.9	0	27	Yes	210	75	Yes	Salt dispersed	Pyrogen tube split; low P operation
-28	0.010	6.7	25	⊙, ramp, button	1.93	0.25	1.37	13.0	Phenolic, 15 mil	6.0	0	30	Yes	0	-	-	Salt well dispersed	TA-L-309 fillet used hereafter, pyrogen did not fire
-29	0.033	(27)	25	+, ramp, button	1.54	0.76	1.39	41.9	Phenolic, 15 mil	6.1	0	32	No	530	360	Yes	Foamed salt	Quench signal at 3.3 seconds
-30	0.022	28.7	8	+(x2) ramp, button	0.96	0.50	1.40	27.5	Phenolic, 15 mil	5.9	0	33	Yes	0	-	-	Salt well dispersed	Grain did not fire

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TABLE A-1 (CONTINUED)

VBA No	QCR, lbs/in²	DCR, lb/lb	Detasheet Thickness, mil	Detasheet Shape	Detasheet Weight, g	Salt Charge Height, in	Salt Charge Density, g/cc	Salt Charge Weight, g	Insulator	Standoff Distance, in	Incidence Angle, degrees	Vacuum Level, mm	Detasheet Initiated	Pressure At Quench Signal	Pressure Reduced To	Burnout	Residues	Remarks
-31	0.034	(64)	-	ramp, button	0.66	0.76	1.39	42 1	Phenolic, 15 mil	6.1	0	31	No	560	480	Yes	Foamed salt	
-32	0.046	57 8	8	+ (x2), ramp button	0.97	1.02	1.36	56 0	Phenolic, 15 mil	6.0	0	32	Yes	540	140	Yes	Foamed salt	
-33	0 022	13 3	25	⊙, ramp, button	2 06	0.50	1.41	27.5	Phenolic, 15 mil	6.1	0	32	Yes	520	90	Yes	Foamed salt	Probably plugged nozzle immediately after quench signal
-34	0.045	(28)	25	○, ramp, button	2.04	1.02	1 36	56.2	Phenolic, 15 mil	6.0	0	32	No	520	465	Yes	Foamed salt	
-35	0.034	(13)	45	○, ramp, button	3.15	0.76	1 38	42.1	Phenolic, 15 mil	6 0	0	30	No	520	-	Yes	Salt not broken	
-36	0.045	87	-	ramp, button	0.65	1.02	1.36	55.9	Phenolic, 15 mil	6.0	0	30	Yes	565	190	Yes	Foamed salt	
-37	0.011	12.9	25	⊙	1.08	0.26	1.39	13.9	Phenolic, 15 mil	6.0	0	18	Yes	530	15	Yes	Salt well dispersed	In-line salt stick housing used hereafter
-38	0.022	28.1	25	○	0.98	0.50	1.40	27.6	Phenolic, 15 mil	6 0	0	30	Yes	570	90	Yes	Foamed salt	
-39	0.011	(7)	45	○	2.04	0.25	1 39	14.1	Phenolic, 15 mil	6.0	0	18	No	590	-	-	Salt not broken	
-40	0.034	27.0	45	+	1.60	0.76	1.40	43.1	Phenolic, 15 mil	6.0	0	25	Yes	520	170	Yes	Foamed salt	
-41	0.023	12 2	45	○	2.34	0.50	1.40	28 5	Phenolic, 15 mil	6 0	0	28	Yes	540	0	No	Foamed salt	
-42	0.034	13 8	8/45	○/○(x2/x1)	3.13	0.76	1.39	43 0	Phenolic, 15 mil	6.0	0	32	Yes	660	65	Yes	Foamed salt	
-43	-	(10)	8/45	○/○	2.77	0.54	1.34	28 9	WRP-X-AQ	-	-	—	No	700	-	-	Chunks of salt, insulator shredded	700 psig dry N_2 used
-44	-	(10)	8/45	○/○	2.83	0.49	1.45	28.7	WRP-X-AQ	-	-	—	No	700	-	-	Chunks of salt, insulator shredded	700 psig dry N_2 used
-45	-	10	8/45	○/○	2.79	0 49	1.47	28.7	WRP-X-AQ	-	-	—	Yes	700	-	-	Salt well dispersed, 60% -30	700 psig dry N_2 used
-46	0.011	(10)	25	○	1.34	0.25	1.40	13.8	WRP-X-AQ	6.0	0	26	No	610	-	Yes	Salt intact	E106 did not fire
-47	0 017	10 2	45	⊙	2.10	0.38	1.36	21.3	WRP-X-AQ	6.0	0	30	Yes	540	55	Yes	Foamed salt	
-48	0.011	(7)	45	○	1.97	0.25	1.36	13.7	WRP-X-AQ	6.0	0	30	No	560	385	Yes	Foamed salt	
-49	0.023	(10)	8/45	○/○	2.75	0.53	1.34	28 3	WRP-X-AQ	5.9	0	33	No	700	-	Yes	Foamed salt and chunks	
-50	0.017	(7)	25/45	+/○	3.06	0.37	1.46	21 3	WRP-X-AQ	5 9	0	32	No	490	-	Yes	Chunks in foamed salt	E106 cocked in holder
-51	0.023	(7)	45	+/○	4.04	0.53	1.36	28.6	WRP-X-AQ	5.9	0	33	No	520	-	Yes	Salt chunks	
-52	0.011	7 2	45	⊙	1.99	0 25	1.40	14 3	WRP-X-AQ	6.0	0	32	Yes	520	80	Yes	Foamed salt	Al backing washer used in det. holder hereafter
-53	0.017	7.1	8/45	○(2x)/⊙	2.98	0.37	1.40	21.1	WRP-X-AQ	6.0	0	29	Yes	605	0	No	Few foamed chunks	Rupture disc blew
-54	0.023	7.1	45	+/○	4.07	0 50	1.40	28.7	WRP-X-AQ	5 9	0	34	Yes	730	0	Yes	Salt well dispersed	Rupture disc blew, reignition and low pressure operation to burnout
-55	0.023	27.2	25	○	1 06	0.50	1.40	28.8	WRP-X-AQ	12.0	0	33	Yes	370	45	Yes	Foamed salt chunks	Pyrogen tube blew, low P operation, reignition within 3 secs after quench signal
-56	0.017	28 2	25	○	1.02	0.51	1 39	28 8	WRP-X-AQ	6 0	45	34	Yes	455	0	Yes	Foamed salt chunks	Reignition at about 10 seconds after quench signal
-57	0.023	13.4	45	○	2.14	0.50	1.40	28.7	WRP-X-AQ	12.0	0	36	Yes	480	20	Yes	Foamed salt chunks	Reignition at about 3.5 seconds after quench signal
-58	0.010	(13)	45	○	2 23	0 51	1.38	28 9	WRP-X-AQ	6.0	45	34	No	560	400	Yes	Foamed salt chunk	
-59	0.023	7.0	8/25/45	○(2x)/○/○	4 10	0.50	1.40	28.6	WRP-X-AQ	11.9	0	34	Yes	520	180	Yes	No foamed chunks recovered	
-60	0.016	7.0	8/25/45	○(2x)/○/⊙	4 11	0 50	1.41	28.9	WRP-X-AQ	6.0	45	36	Yes	520	260	Yes	Foamed salt chunks	
-61	0.017	14.3	8/25	○/○	1.49	0.37	1.40	21.3	WRP-X-AQ	6.0	0	38	Yes	475	45	Yes	Foamed salt chunks	
-62	0.016	13.6	45	○	2.12	0.51	1.39	28.7	WRP-X-AQ	6.0	45	38	Yes	455	0	No	Foamed salt chunks	Burst disc ruptured
-63	0.017	29.1	8	○(2x)	0.73	0.38	1.39	21.3	WRP-X-AQ	6.0	0	36	Yes	345	30	Yes	Foamed salt chunks	Low pressure operation due to broken pyrogen tube
-64	0.016	10.0	25/45	○/○	2.89	0.50	1.42	29.0	WRP-X-AQ	6.0	45	39	Yes	515	10	Yes	Foamed salt chunks	Reignition within 1 second after quench signal
-65	0.012	28.6	8	○(2x)	0.50	0.25	1 40	14.4	WRP-X-AQ	6.0	0	39	Yes	725	105	Yes	Foamed salt chunks	
-66	0.017	6.9	25/45	○/○	3.07	0.37	1.41	21.2	WRP-X-AQ	6.0	0	39	Yes	525	85	Yes	Foamed salt chunks	
-67	0.022	(28)	25	○	0.97	0 50	1.38	27 4	WRP-X-AQ	12.0	0	40	No	-	-	-	Quench charge intact	Quench signal not applied, low pressure operation
-68	0.023	5.9	45	○(2x)	3.96	0.40	1.40	27.4	WRP-X-AQ	5.9	0	39	Yes	510	0	No	No foamed chunks recovered	Pressure terminal blew out

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FOLDOUT FRAME 1

FOLDOUT FRAME 2

APPENDIX B

PRELIMINARY FULL-SCALE ATTA MOTOR DESIGN

Full-Scale, Flightweight ATTA Motor Designs. Preliminary designs for two-pulse, single-quench and two pulse, double-quench full-scale ATTA motors are depicted by Figures B-1 and B-2. Motor weight data are presented in Table B-I.

Typical pressure, thrust, and payload acceleration versus time for the operation of the proposed two-pulse, single-termination ATTA system on a modified STAR 37D motor are presented on Figure B-3. The single termination is shown at 23 seconds, which is about 50% of the total burn time. When salt is injected into the motor a momentary rise in pressure and thrust of about 20 percent may occur due to the discharge of a portion of the salt out the nozzle before combustion is extinguished. After termination begins, depressurization of the chamber will drop the operating pressure level about 90 percent in about 100 to 200 milliseconds.

Performance curves illustrating the operation of the two-pulse, two-termination ATTA system on a modified STAR 37D motor are presented on Figure B-4. The two terminations are shown at times representing 50 and 98 percent of the total burn time.

The well-proven STAR 37B (TE-M-364-2 Burner II)/STAR 37D (TE-M-364--3 Delta) design has been selected for adaptation to the ATTA configuration for reasons of overall program economy. Flightweight cases are available at no cost to JPL for later program phases and the 1400 lbm propellant weight will hold costs down. Further, the solid quench ATTA design can be subsequently incorporated into the similar STAR 37E (TE-M-364-4) or STAR 37G (TE-M-364-11) Extended Delta rocket motors as additional impulse capability is required. The Extended Delta motors are loaded to a nominal 2300 lbm propellant weight. Figure B-5 illustrates the configurations of the STAR 37 (TE-M-364) motors.

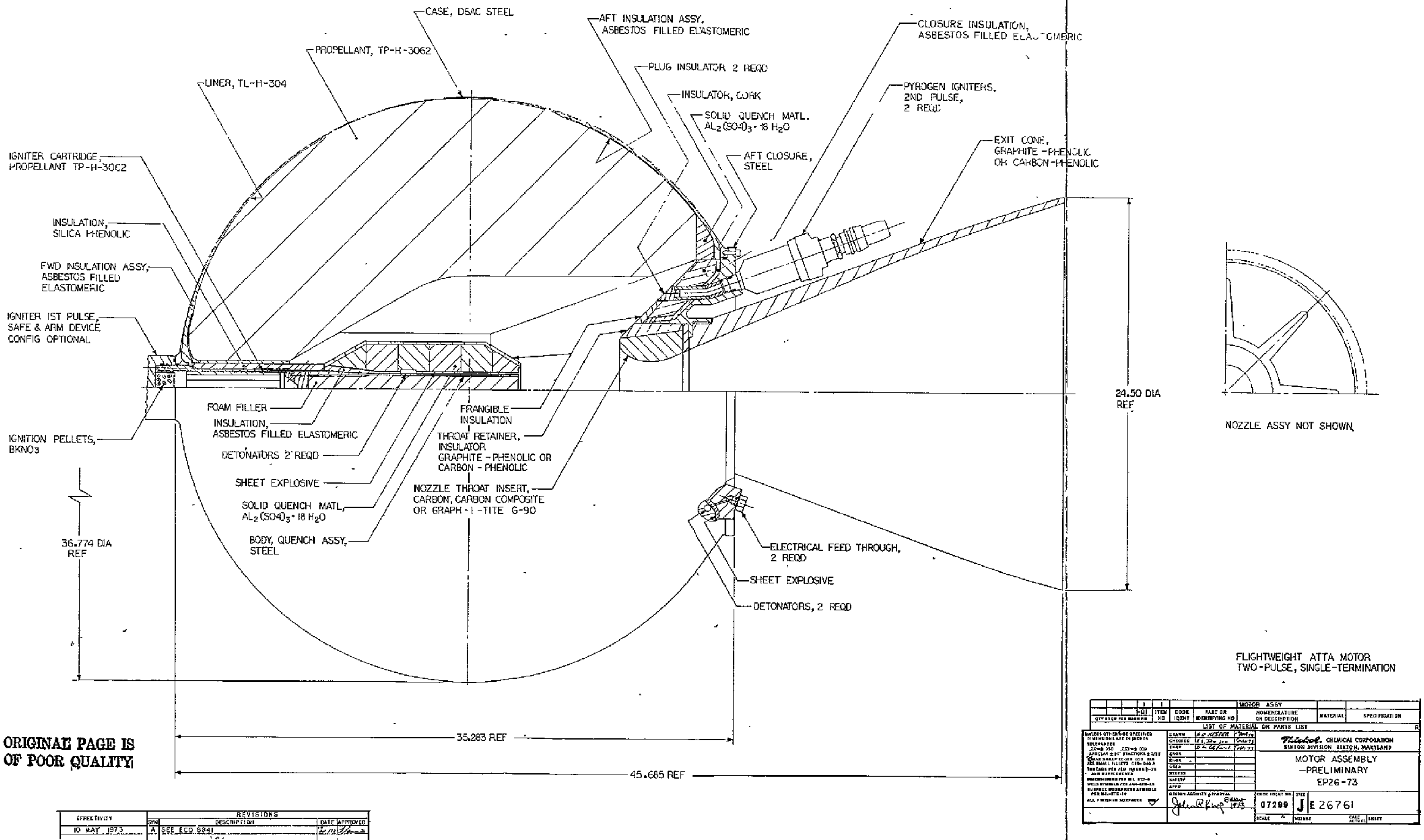

FIGURE B-1. TWO-PULSE, SINGLE-TERMINATION FLIGHTWEIGHT ATTA MOTOR

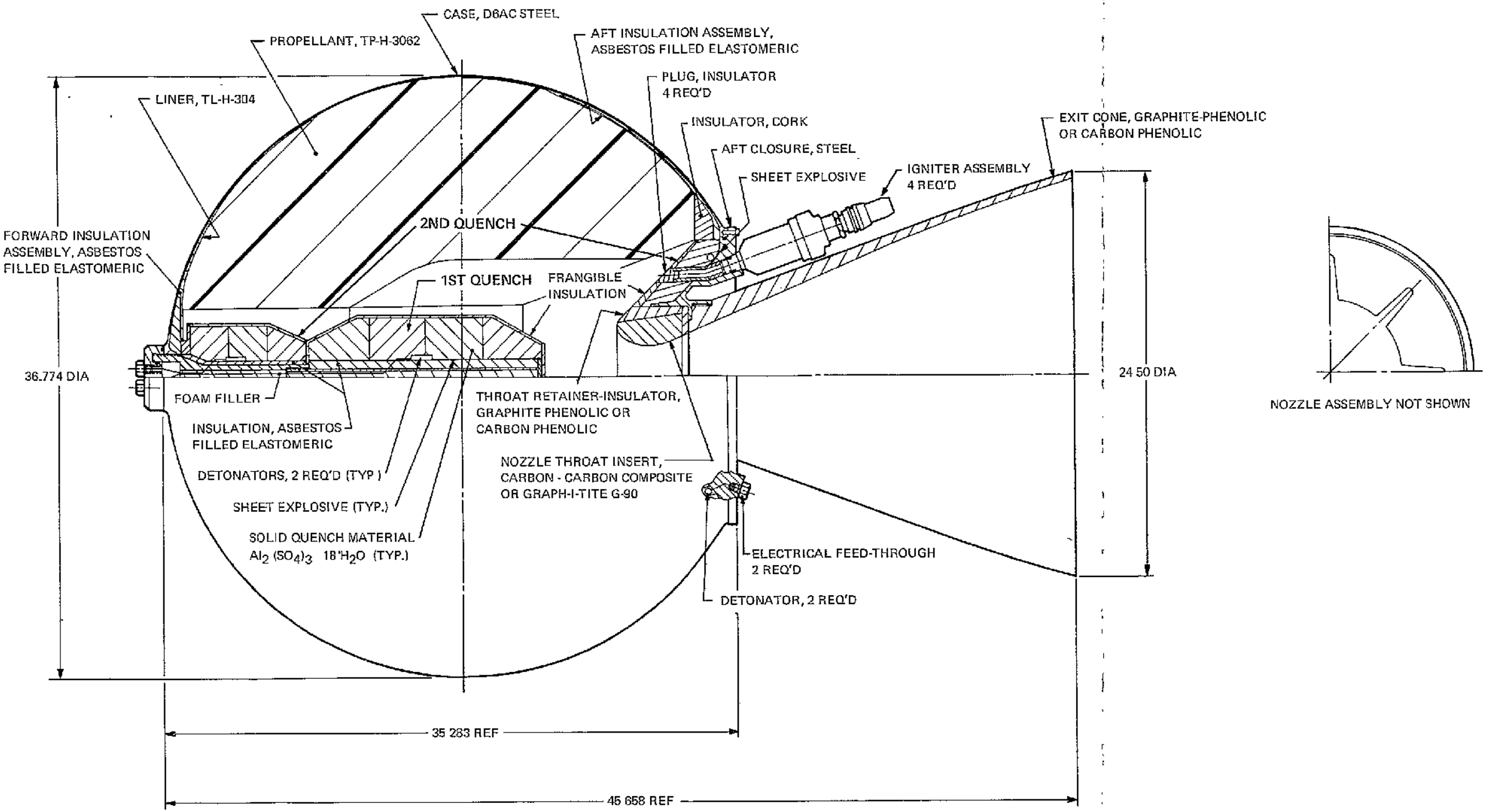

FIGURE B-2. TWO-PULSE, TWO-TERMINATION FLIGHTWEIGHT ATTA MOTOR

TABLE B-1

FLIGHTWEIGHT ATTA MOTOR WEIGHT SUMMARY:
TWO-PULSE, SINGLE-TERMINATION AND
TWO-PULSE TWO-TERMINATION CONFIGURATIONS

Item	Nominal Weight, lbm	
	Two-Pulse, Single-Term.	Two-Pulse, Two-Term.
Case Assembly(1)	73.0	73.0
Case Insulation	30.0	30.0
Nozzle/Closure Assembly(2)	90.0	90.0
Igniter, Head End	4.0	-
Igniters, Aft End	3.5(3)	7.0(4)
Quench Assembly, Head End	16.0(5)	37.0(6)
Quench Assembly, Aft End	12.5	12.5
Safe-and-Arm Devices(7)	10.0	10.0
Liner	1.5	1.5
Misc. (O-Rings, Fasteners)	2.0	2.0
TOTAL, EMPTY MOTOR	242.5	263.0
Propellant	1400.0	1360.0
TOTAL, LOADED MOTOR	1642.5	1623.0
Propellant Mass Ratio	0.853	0.838

(1)Weight based upon STAR 37B Burner II motor case.
(2)Nominal weight for 50/1 nozzle expansion ratio.
(3)Weight for two redundant igniter assemblies.
(4)Weight for four igniter assemblies (two redundant pairs).
(5)Weight includes 12.5 lbm $Al_2(SO_4)_3 \bullet H_2O$ material and 3.5 lbm inerts.
(6)Weight includes 32 lbm $Al_2(SO_4)_3 \bullet H_2O$ material and 5.0 lbm inerts.
(7)Weight estimate provided for two electro-mechanical safe-and-arm devices.

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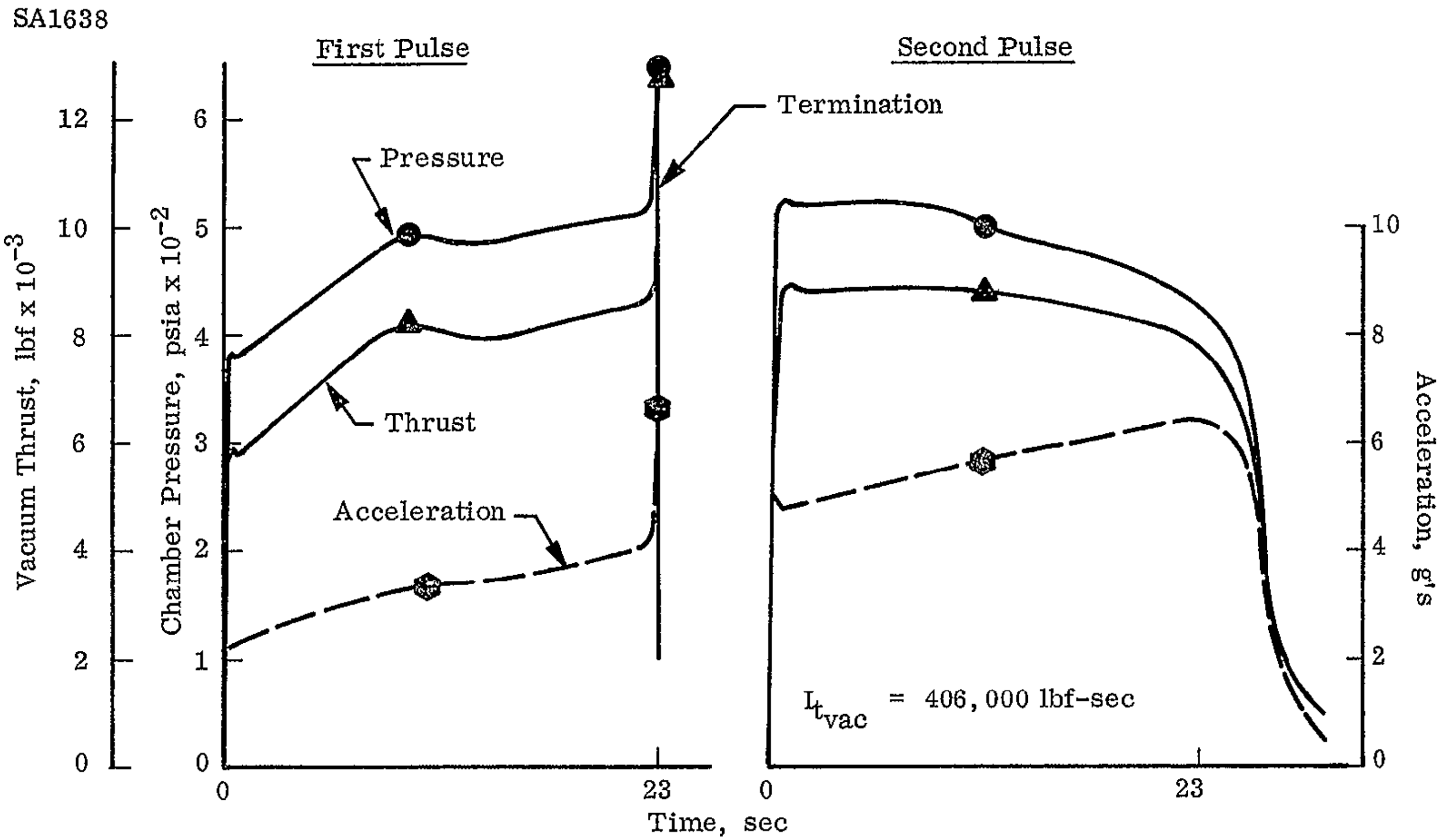
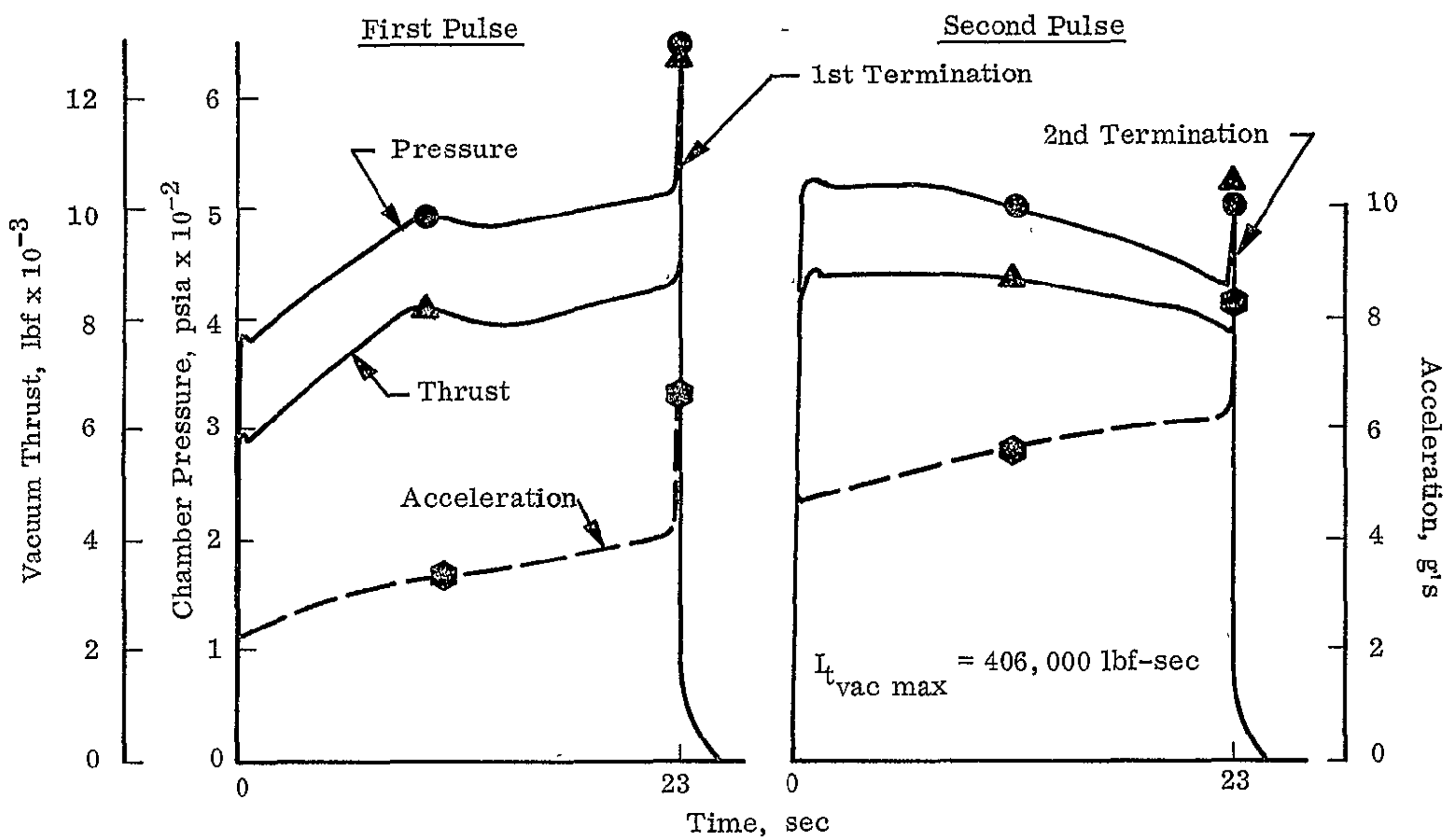


*+70°F Performance With 1000 lbm Payload.

FIGURE B-3. CHAMBER PRESSURE, VACUUM THRUST, AND ACCELERATION* VERSUS TIME: FULL-SCALE, TWO-PULSE, SINGLE-TERMINATION ATTA MOTOR

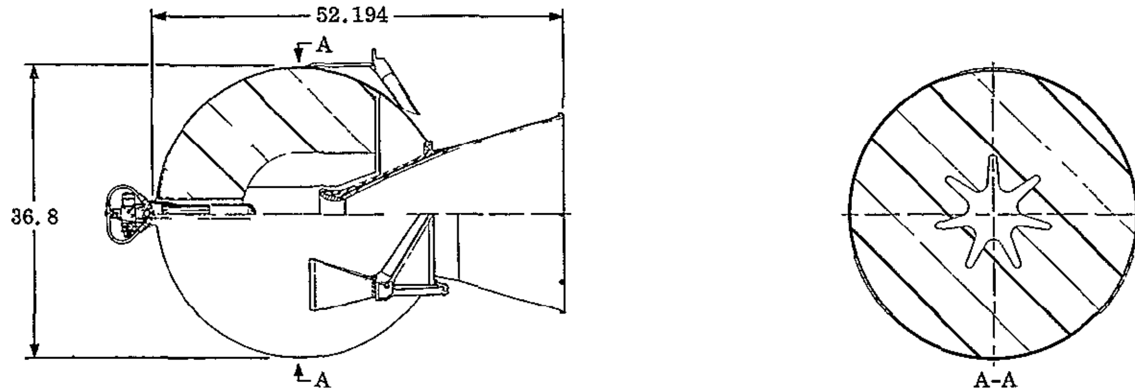
SA1637



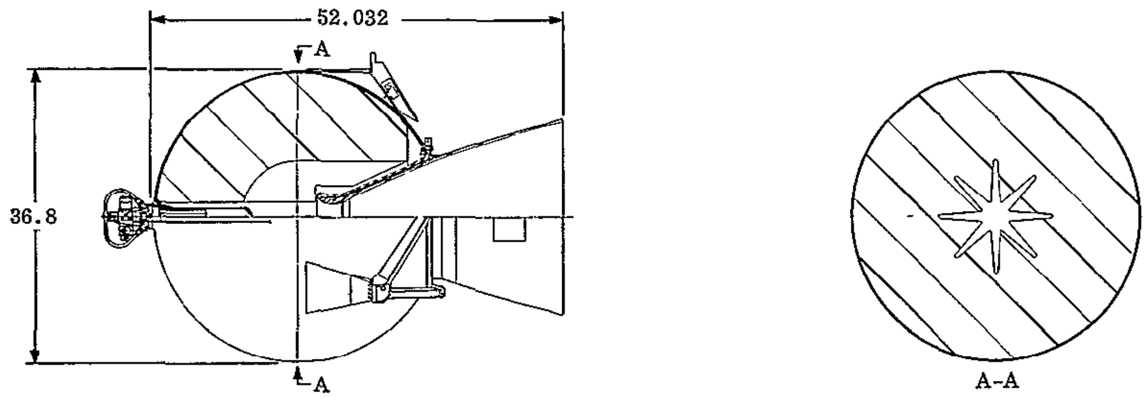
*+70°F Performance With 1000 lbm Payload.

FIGURE B-4. CHAMBER PRESSURE, VACUUM THRUST, AND ACCELERATION* VERSUS TIME: FULL-SCALE, TWO-PULSE, TWO-TERMINATION ATTA MOTOR

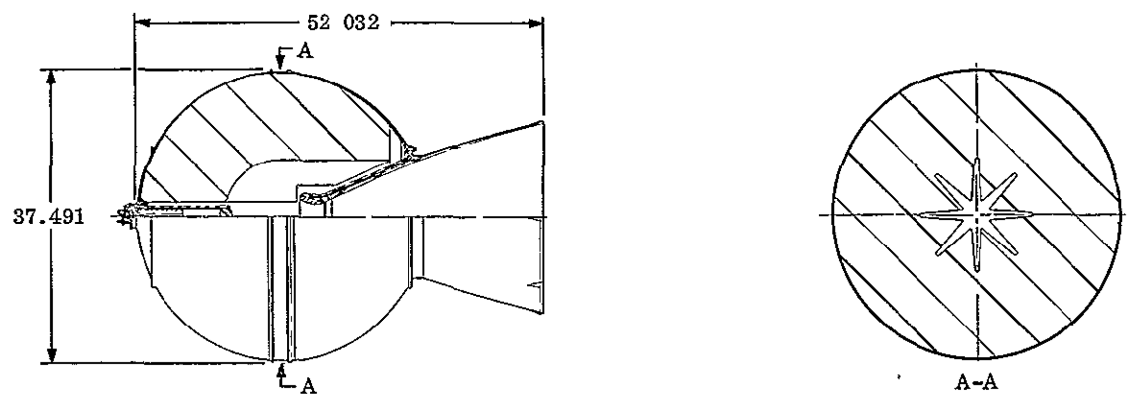
STAR 37 (TE-M-364-1 Surveyor Main Retro)



STAR 37B (TE-M-364-2 Burner II)



STAR 37D (TE-M-364-3 Delta)



STAR 37E/37G (TE-M-364-4/11 Extended Delta)

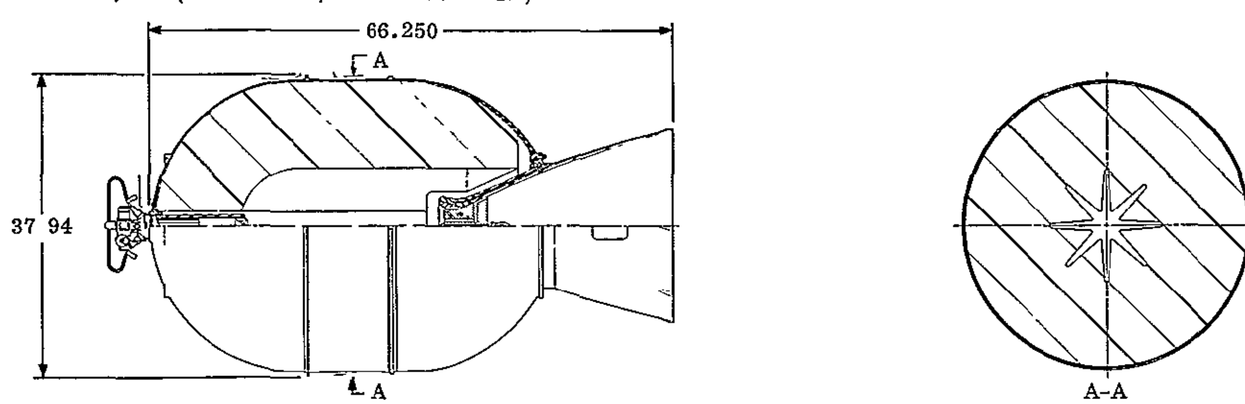


FIGURE B-5. QUALIFIED AND FLIGHT-PROVEN STAR 37 (TE-M-364) SERIES OF 37-INCH-DIAMETER ROCKET MOTOR DESIGNS

Ballistic Performance and Mass Properties, TE-M-364-3 Delta Baseline Motor. Thiokol-Elkton reports RER-413B,"Revised Internal Ballistic Report for TE-M-364-3 Rocket Motor," and RER-423B, "Weight, Balance and Mass Moment of Inertia of the TE-M-364-3 Rocket Motor," define the baseline motor used for the ATTA designs.

Motor Impulse Reproducibility. The +70°F impulse reproducibility of the full-scale ATTA motor will be contingent upon the uniformity of loaded propellant weights, batch-to-batch propellant energy levels, nozzle geometry, and quench effects.

The baseline ATTA motor design, the STAR 37D (TE-M-364-3 Delta), has demonstrated 3-sigma I_{sp} reproducibility levels of 0.23% and 0.26% during flights and test firings. Data are summarized in Tables B-II and B-III. Loaded propellant weight variability has been demonstrated to be approximately ± 1.5 lbm for the Delta and Burner II rocket motors or ± 0.1%.

A review of the aluminum sulfate hydrate motor termination test conducted at Thiokol-Elkton in a TP-H-3062 loaded 5-inch CP motor indicates that the extinguishment of the propellant, the quench-induced cooling of the chamber gases, and the decrease of the chamber pressure from operating to ambient pressure occurred in 0.15 second. This time is comparable to the pressure tailoff transient of a standard TP-H-3062-loaded 5-inch CP motor fired at the same pressure level. Consequently, the principal mechanism which could affect motor impulse reproducibility (or predictibility) is the restart energy absorbed by the residual hydrate material during second-pulse ignition. Since additional energy will be added to the ATTA system by the second-pulse igniters and some unknown quantity of hydrate material will be converted in the vacuum environment between pulses, the net energy exchange effect upon motor impulse must be examined for typical pulse durations and interruptions. It is felt that the termination effects will be predictable for specific ATTA duty cycles.

ATTA Motor Component Design. The philosophy used for the preliminary ATTA motor designs was one of solid quench system adaptation to the STAR 37B (TE-M-364-2 Burner II)/STAR 37D (TE-M-364-3 Delta) motor with minimal design change. Original quench system designs are based on delivery of 0.005 lb of quenchant to each square inch of burning surface. Based on the available test data, it appears that the QCR should be approximately double the original estimate.

Motor Case. The 36.7-inch-diameter, D6AC steel Delta and Burner II motor cases are equivalent designs except at the payload and vehicle attachment interfaces, which are designed for the respective program requirements. The ATTA motor can be configured with either case. A 3-inch-diameter threaded boss is provided in the forward hemisphere

TABLE B-II

I_{sp} REPRODUCIBILITY OF STAR 37D MOTOR IN STATIC TESTS AT AEDC

Motor Serial Number	Propellant Weight, lb	Spin Rate, rpm	Temp., °F	I_{tot}, lbf-sec	I_{sp}, lbf-sec/lbm			Corrected I_{sp} at 75°F, lbf-sec/lbm
T00001	1439.4	110	55	417,923	290.3			290.6
T00002	1438.7	110	95	419,075	291.3			291.0
T00003	1440.6	0	75	418,887	290 8			290 8
T00004	1439,2	0	75	418,252	290.6			290.6
T00005	1441 6	110	75	418,887	290.6			290.6
T00006	1439.9	110	50	417,860	290.2			290.5
T00010	1439.5	110	75	419,153	291.2			291.2
NTV-1	1439 9	110	45	417,594	290.0			290 4
						n	=	8
						$\overline{X}$	=	290 7
						3 σ	=	0 26%

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TABLE B-III

I_{sp} REPRODUCIBILITY OF STAR 37D MOTOR IN DELTA VEHICLE FLIGHTS

W_p = 1440 lb

Vehicle No.			I_{sp}, lbf-sec/lbm
57			290.5
63			290.45
66			290.2
68			290.3
74			290 58
75			290.32
78			290.33
77			290.4
79			290.8
80			289 9
	n	=	10
	$\overline{X}$	=	290 4
	3 σ	=	0 23 %

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for an igniter or quench assembly. A 16.8-inch-diameter boss is incorporated at the aft end of the case for nozzle attachment. The nozzle assembly is attached with 44 5/16-24 UNF bolts. The nominal proof test pressure and ultimate pressure are 707 psia and 1000 psia, respectively. The forward face of the motor case igniter boss will be configured for a face O-ring seal in the event that the forward quench assembly is assembled from the aft end of the loaded case assembly. The preliminary ATTA motor design will be nozzled and insulated to operate at a nominal 500 psia chamber pressure level to accommodate transient pressure increases during termination.

Internal Insulation. The ATTA motor case will be internally insulated with an asbestos-filled elastomeric for thermal pressure vessel protection during motor operation. The insulation will consist of forward- and aft-end assemblies with integral relief boots to provide propellant grain stress relief during cure and temperature cycling. The ATTA insulation design will be similar to the baseline STAR 37D (TE-M-364-3) configuration, except that the insulation will be thickened for dual-pulse operation and TI-R-300 asbestos-filled polyisoprene will be substituted for the V-44 asbestos-filled Buna material used in the Delta unit.

Propellant Grain and Liner. The ATTA propellant grain designs are minor redesigns of the STAR 37D 8-point star configuration. The aft end and bore are modified to accommodate the quench assemblies and to produce burn surfaces which are exposed to quench particle impingement at the intended termination times. The estimated propellant weights are 1400 lbm and 1360 lbm for the single- and double-quench designs, respectively. The TL-H-304 liner is used to enhance insulation bonding.

Nozzle Assembly. The nozzle is an enlarged version of the semi-submerged design currently in use on 13.5- through 27.3-inch-diameter STAR motors illustrated in Figure B-6. Its key feature is primary structural dependence on the metal closure.

The steel closure is the major nozzle structural element. All blowout loads from the throat insert are transmitted directly through the backup ring into the closure. No blowout loads are transmitted to the exit cone. SAE 4130 steel was selected as the closure material because of its cost, fabrication characteristics, and strength. The part will be template-machined from a simple forging.

The nozzle exit cone will be fabricated from bias-cut carbon tape phenolic or graphite tape phenolic. The standard prepreg materials, such as U. S. Polymeric FM-5063 and FM-5064, and high-carbon-yield resin prepregs such as FM-5441 will be considered for the multiple-pulse ATTA applications. Tape-wrapping is the best method of construction for lightweight cones of this size. The tape bias angle and tape ply-to-centerline angles will be optimized to enhance cone strength and to provide a high ratio of virgin-to-charred material in each ply.

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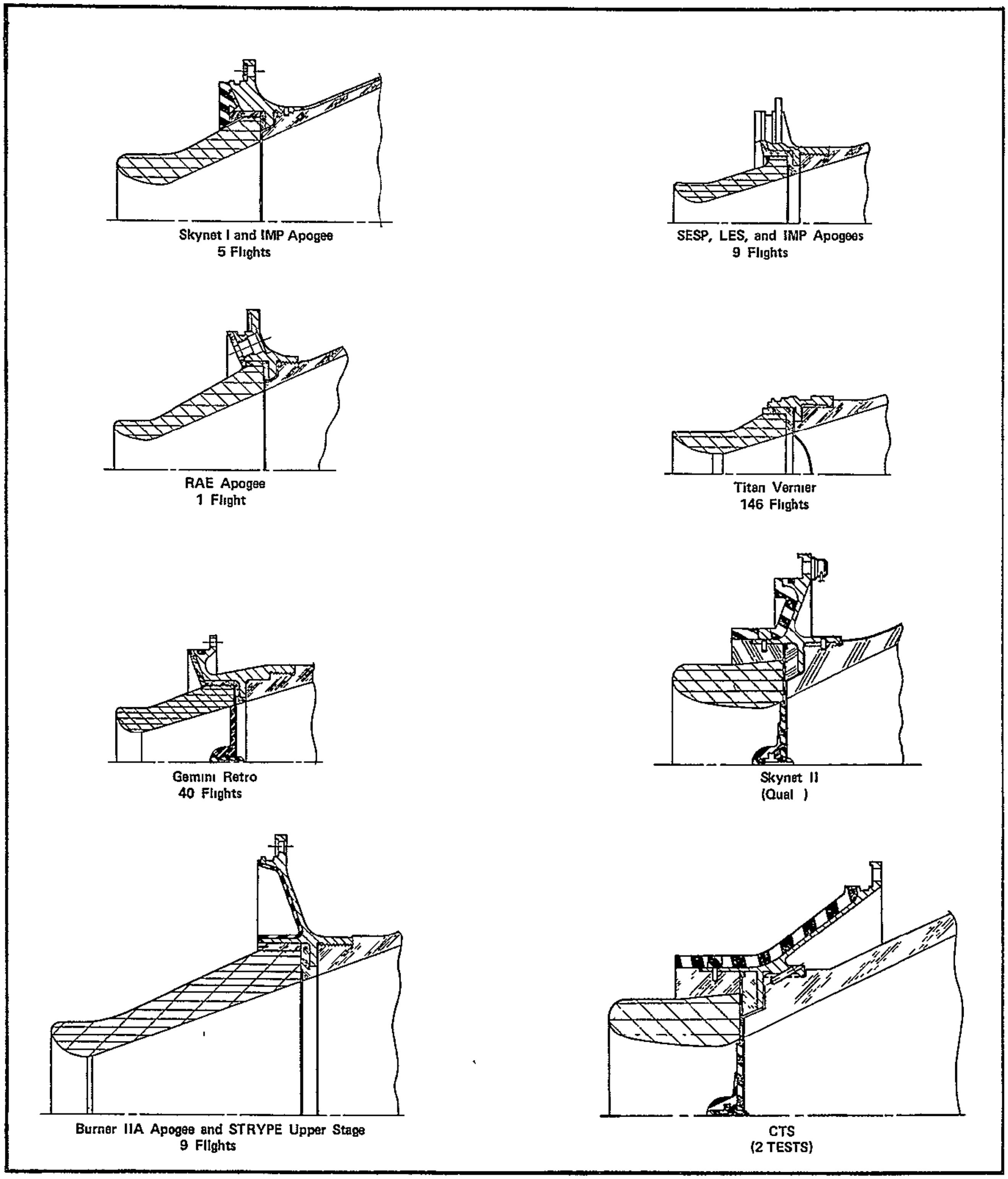

FIGURE B-6. EXPERIENCE BACKGROUND FOR DOMSAT MOTOR NOZZLE STRUCTURE

Ignition Assemblies. Head-end- and aft-end-mounted pyrogen igniters have been designed for the preliminary ATTA motor. The first pulse igniter shown for the two-pulse single-quench ATTA motor on Figure B-1 is the standard STAR 37 pyrogen design integrated into a head-end-mounted, ignition/quench assembly. The silica-phenolic igniter nozzle is equipped with six canted nozzles which direct the igniter output through the case and external insulation to impinge on the motor propellant grain. The TP-H-3062 igniter cartridge is initiated by two redundant electrical ignition cartridges or two through-bulkhead initiators and a $BKNO_3$ pellet charge. The igniter output is approximately 1 lbm/second for a 0.6-second duration.

Two aft-end, redundant TP-H-3062 loaded pyrogen igniters are provided for the second motor pulse. These are sized to provide 50 percent more output than the head-end igniter to compensate for the additional motor free volume and quench material present during motor re-ignition. Seal plug insulators are used in the blast tube ports of the second pulse igniters.

The detailed design of the ignition safe-and-arm devices will be accomplished when the ATTA motor system requirements are defined. A weight allocation of 10 lbm was used in the ATTA weight summaries for the ignition and quench system safe-and-arm devices.

Quench Assemblies. Three preliminary quench assemblies have been designed for the flightweight ATTA motors. The head-end-mounted, single-termination quench assembly in Figure B-1 consists of 12.5 lbm of compression-molded aluminum sulfate hydrate segments bonded to an externally insulated tubular steel holder, equipped with sheet explosive and two detonators. The inside of the tubular steel holder is filled with urethane foam to minimize heat input to the sheet explosive and detonators through the ends of the quench assembly. The outer surfaces of the quench material are protected by a frangible insulator. The quench assembly is installed in the rocket motor as part of the integrated ignition/quench assembly.

The head-end-mounted quench assembly depicted in Figure B-2 has the same basic design features as the single termination configuration, except that the igniter has been replaced with a second quench unit which will be initiated simultaneously with the nozzle-mounted quench assembly for the second termination. A total of 32 lbm of aluminum sulfate hydrate quench material is provided on the head-end assembly for the first and second terminations.

The nozzle-mounted quench assembly utilizes compression-molded aluminum sulfate hydrate segments, sheet explosive, two detonators, and a frangible external insulation as described for the head-end quench assemblies; however, the metal nozzle closure will be incorporated as the quench holder for the aft-end unit. A 12.5-lbm salt charge is provided on the aft injector assembly for both the single- and two-termination designs. An elastomeric insulator is used between the sheet explosive and the nozzle closure on the single-termination design to protect the nozzle structure during the second motor pulse.

Since the ATTA motor pulse durations are undefined to date, the quench material weights utilized for the preliminary designs were based upon full duration motor operation for the single-termination and second-termination quench units.

$$\text{Quench Wt. (lbm)} = A_s\ (\text{in.}^2) \times 0.011 \left(\frac{\text{lbm}}{\text{in.}^2}\right)$$

$$= 2000\ (\text{in.}^2) \times 0.011 \left(\frac{\text{lbm}}{\text{in.}^2}\right)$$

$$= 24.8 \text{ lbm Quench Material}$$

The first termination of the two-termination designs was assumed to occur after 60% of the propellant web had been consumed.

$$\text{Quench Wt. (lbm)} = 2000\ (\text{in.}^2) \times 0.011 \left(\frac{\text{lbm}}{\text{in.}^2}\right)$$

$$= 19.5 \text{ lbm Quench Material}$$

3.2 Subscale ATTA Motor Design. The four fundamental design tasks which must be solved to successfully incorporate a one- or two-termination pulse capability in a subscale or a full-scale space motor are:

1) The design of a propellant grain with a burn surface geometry that is totally exposed to the motor centerline at moderate incidence angles (45° or less).

2) A quench system which will afford complete burn surface area coverage by the quench material at moderate incidence angles.

3) Thermal and erosion protection of the quench material to preclude degradation before termination with minimum effect upon particulate distribution.

4) Quench system designs that will not degrade motor integrity and reliability at the time of termination or during subsequent motor operation.

The most difficult task that will be encountered is accomplishing an integrated propellant grain and quench system design which will deliver aluminum sulfate hydrate to all propellant burn surfaces for two discrete terminations. The brisant effect of the sheet explosive will require complete separation of the two quench units or protection of the passive adjacent quench assembly during the first pulse termination.

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